

Utilization of Modeling and Simulation in Lower Extremity Injury Analysis

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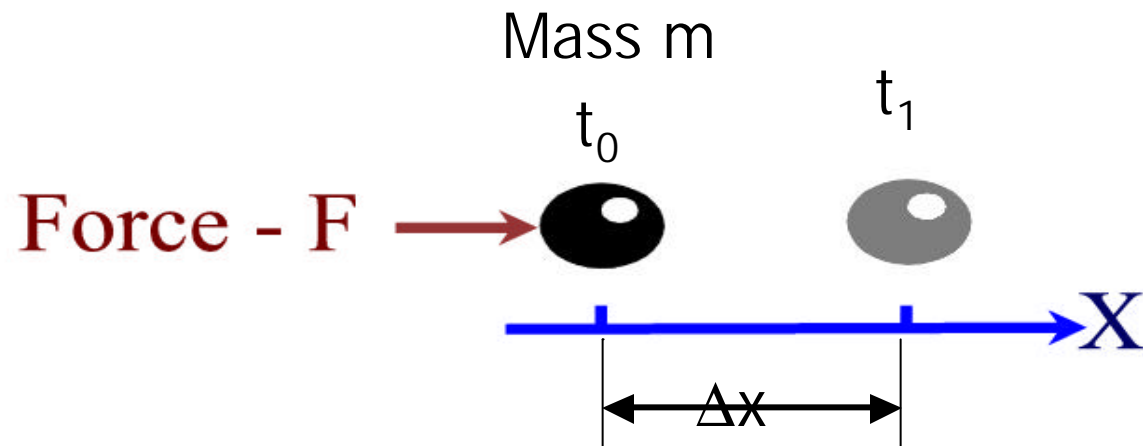
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Outline

- Lump Mass Modeling 101
- Data Sources
- Upper Leg Injury – Case Study
- Lower Leg Injury – Case Study

Lumped Mass Modeling 101



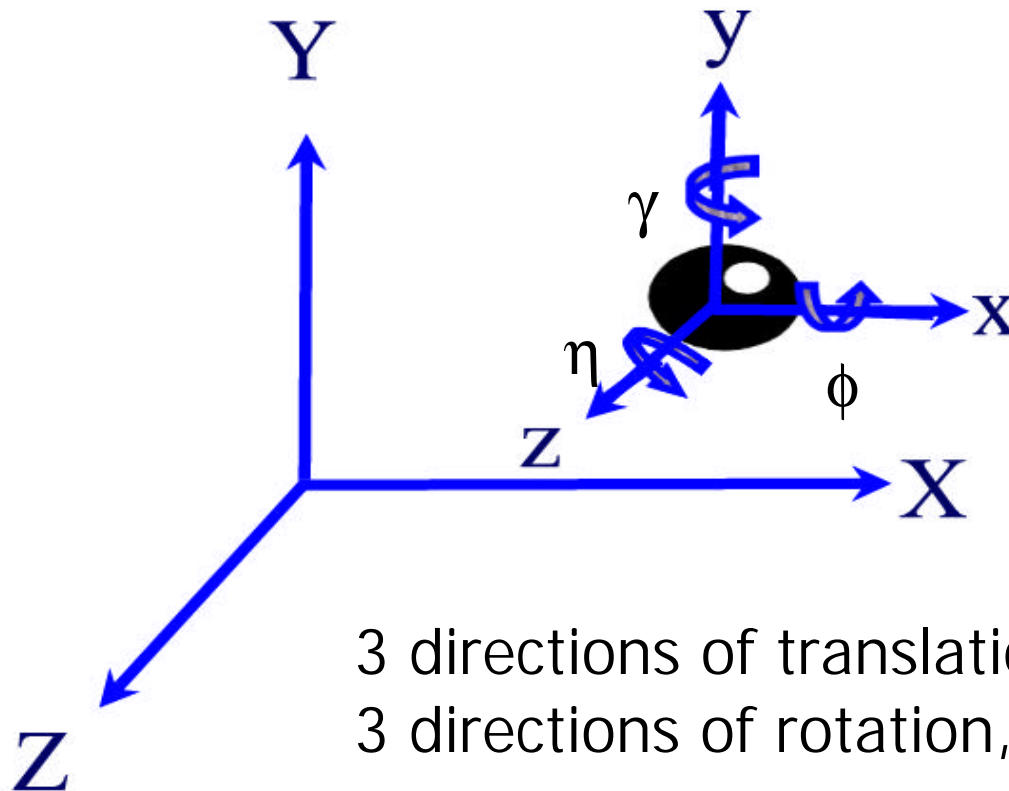
$$\Delta v = a \times \Delta t$$

$$\Delta x = \frac{1}{2} \Delta v \times \Delta t = \frac{1}{2} a \Delta t^2$$

$$a = F/m; \quad \Delta x = \frac{1}{2} F/m \Delta t^2$$



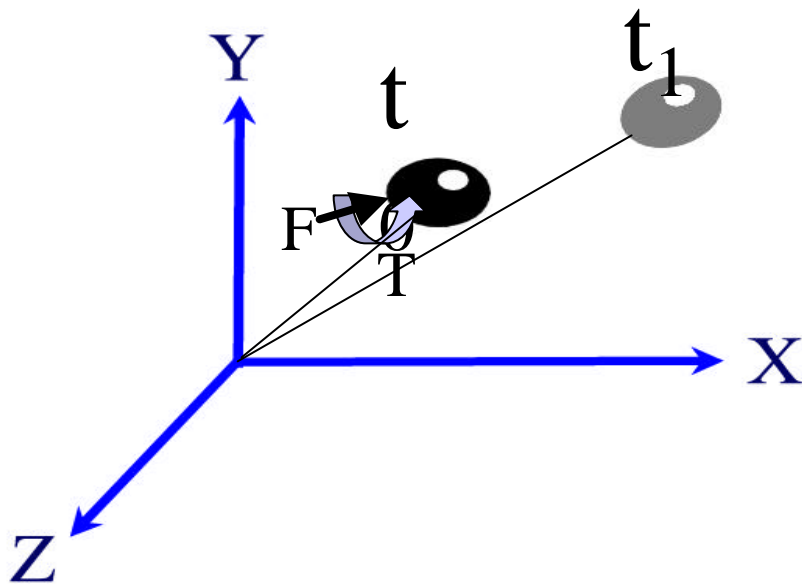
Degrees of Motion for Models



3 directions of translation, x, y, z
3 directions of rotation, ϕ, γ, η



Lumped Mass Modeling Approach



Apply single degree relationships to:

X, Y, Z for Linear Displacements

ϕ, γ, η for Angular Displacements



Forces Are Not Constant With Displacement

Modeling Requires Force Vs.
Displacement Relationships

- Force = $K(x)$ Hook's Law
- Torque = $k r(\phi)$



Modeling Requires More Than One Mass

- Add masses connected by joints
- Add geometric compatibility relationships



Add Lumped Masses Connected by Joints

Applicable Laws and Principles:

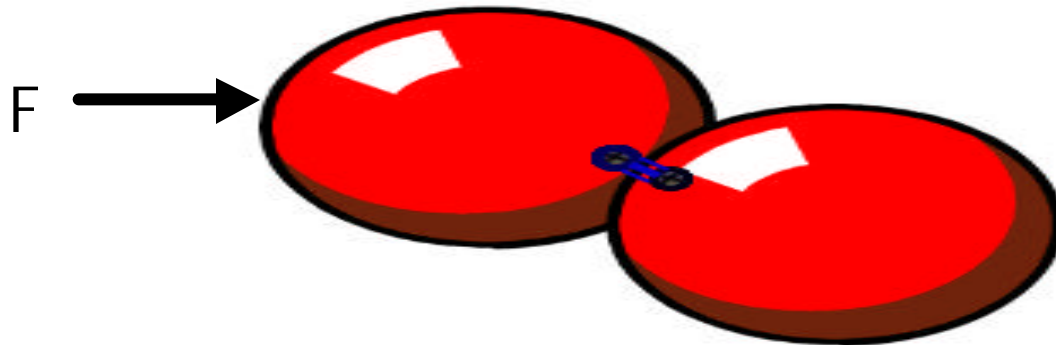
Newton's 1st Law; $F = ma$; $T = I\alpha$

Force & Torque Equilibrium; $\Sigma F = 0$; $\Sigma T = 0$

Force vs Displacement Relationships

Geometric Compatibility; Joint Constraints

Two Segments Connected by a Joint





Typical Joints for Modeling

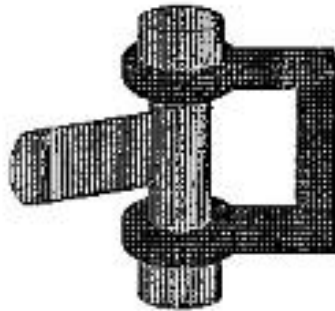
Ball & Socket or Free



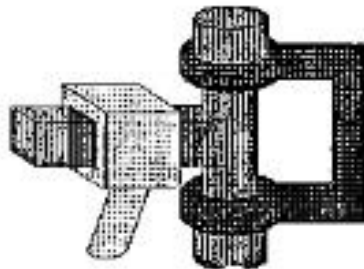
**Slip With Rotation
About Z Axis**



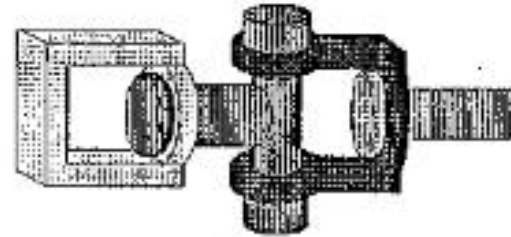
Pin (Hinge)



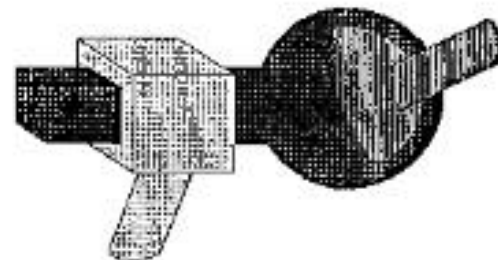
**Slip With Rotation
About Y Axis**



Euler

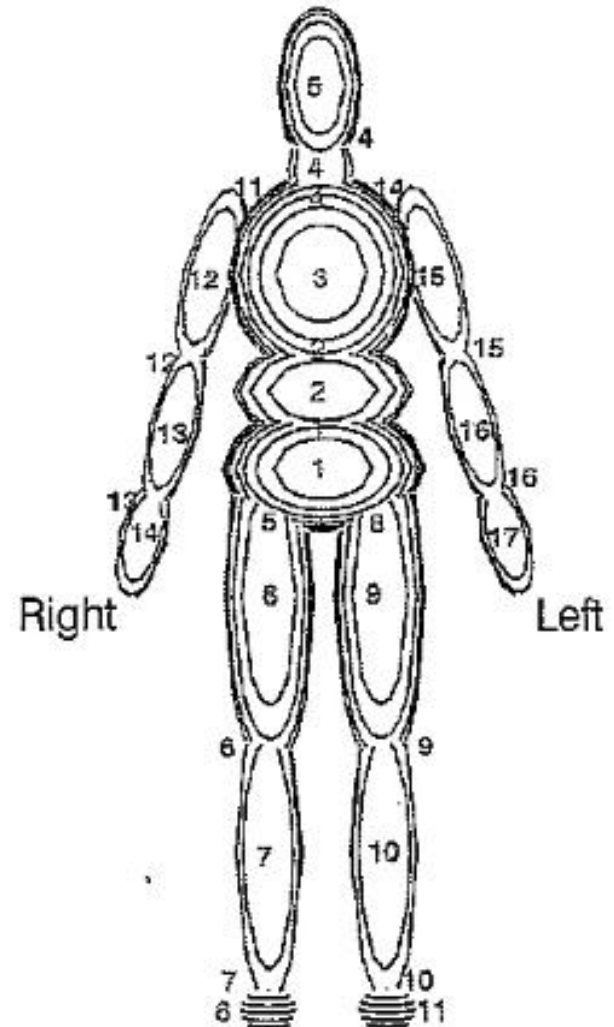


**Slip With Complete
Angular Freedom**



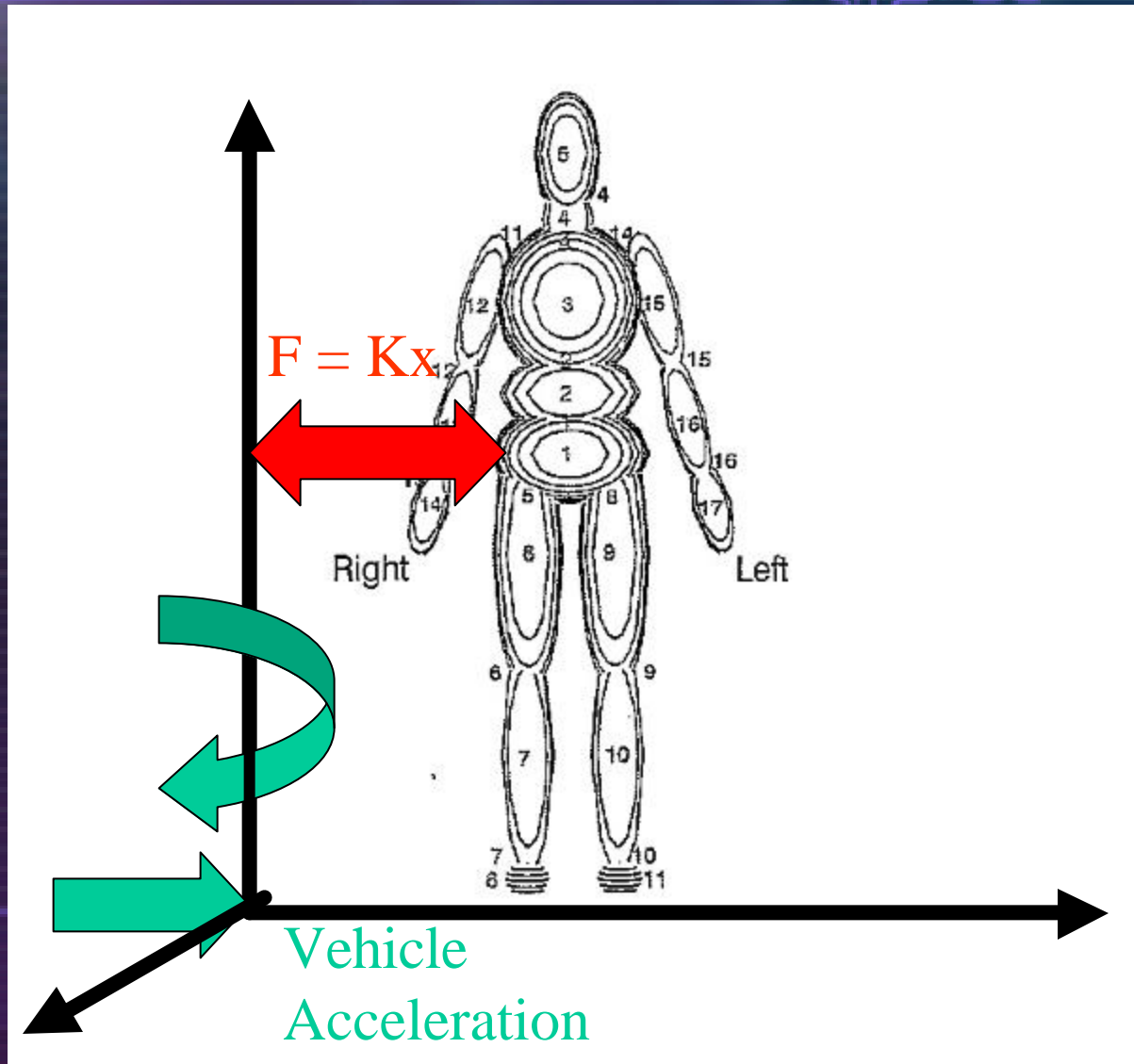


Hybrid III Dummy Model 17 Masses & 16 Joints





Input - Vehicle Acceleration vs Time & Force Displacement Relationships



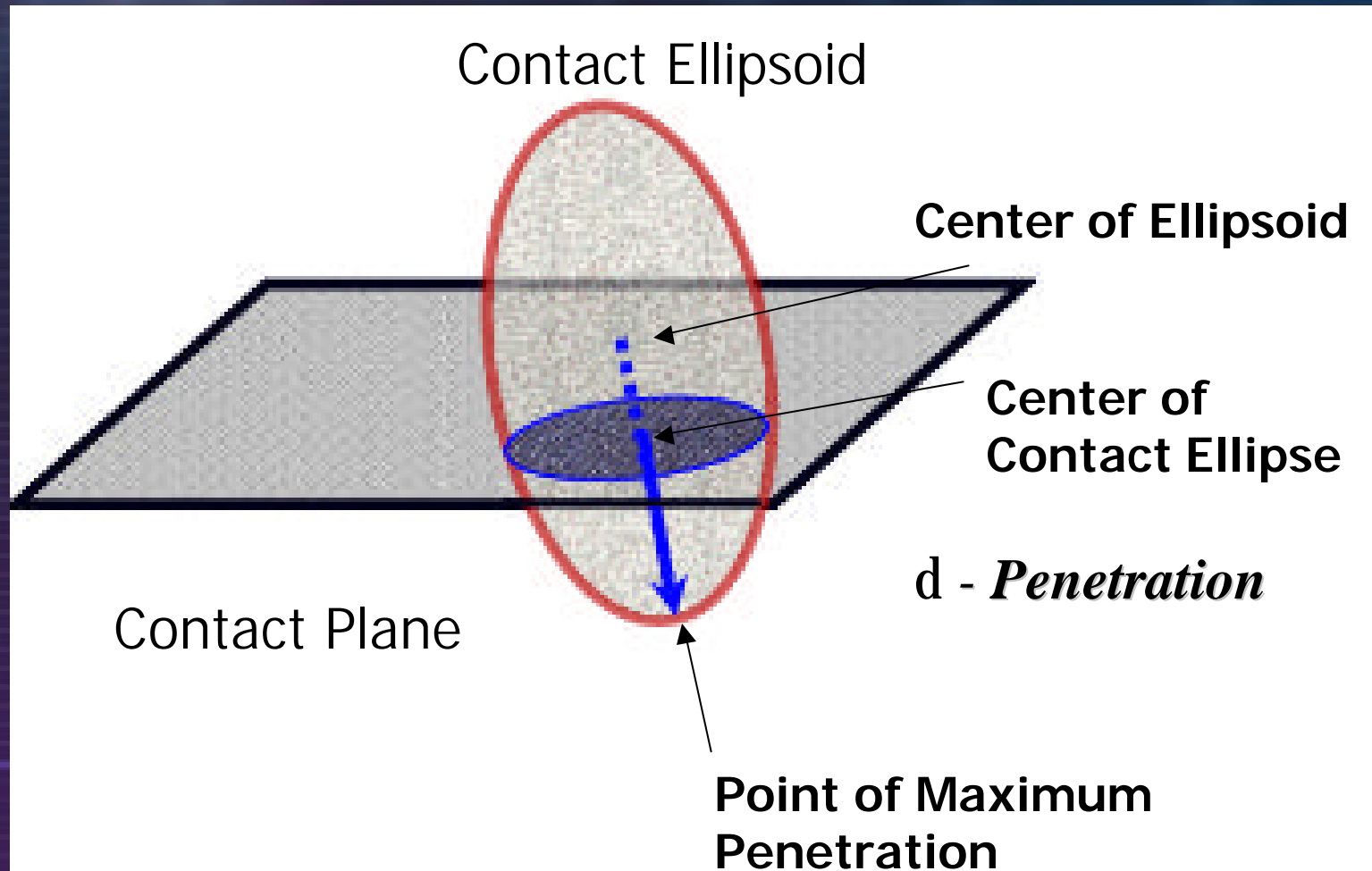


Force Displacement Relationships

- Body segment surfaces represented by ellipsoids
- Vehicle surfaces represented by either:
 - Planes
 - Ellipsoids
 - Hyper-ellipsoids
- Contact forces represented by penetration of vehicle surfaces by body ellipsoids

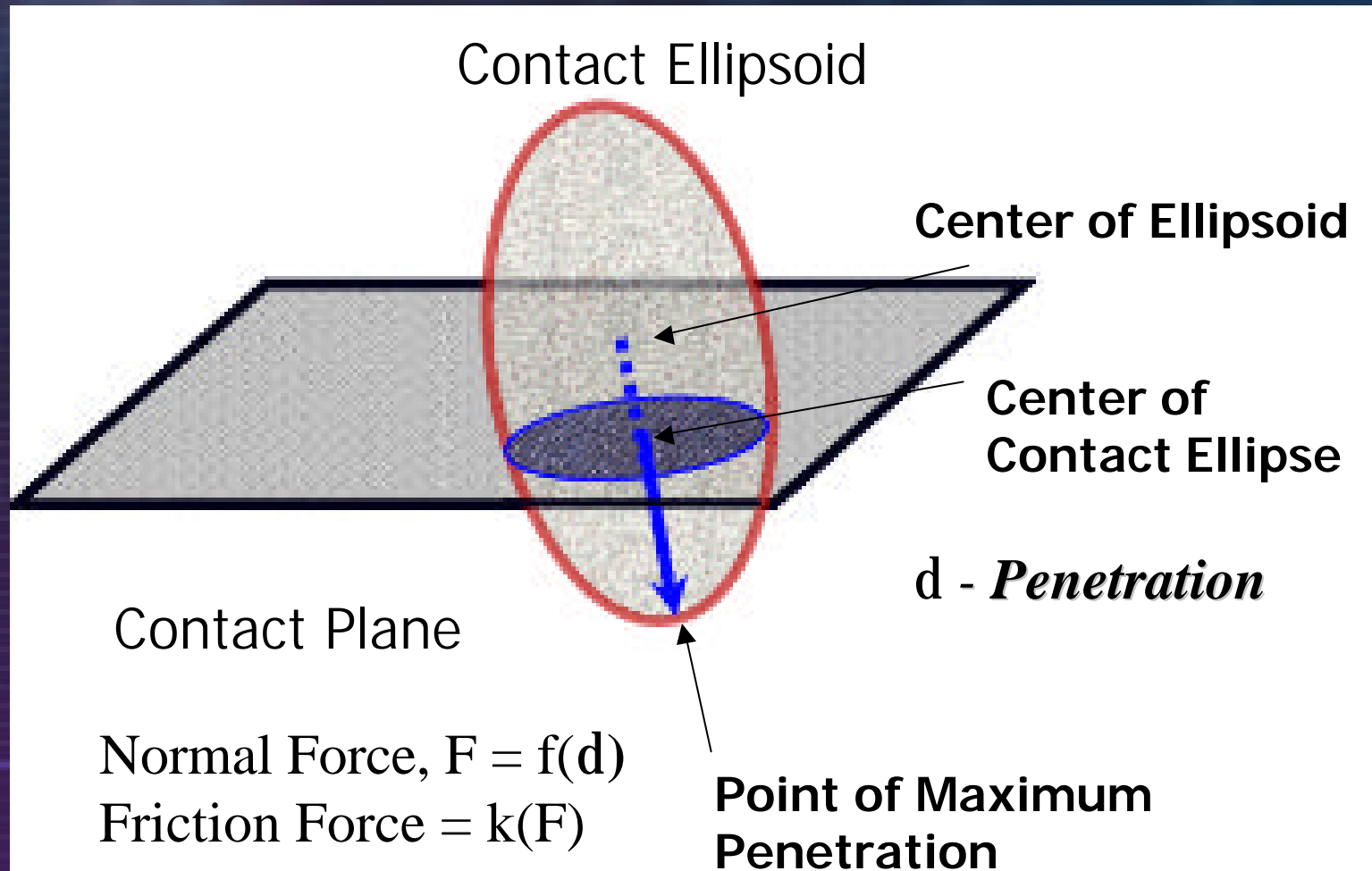


Definition of Penetration





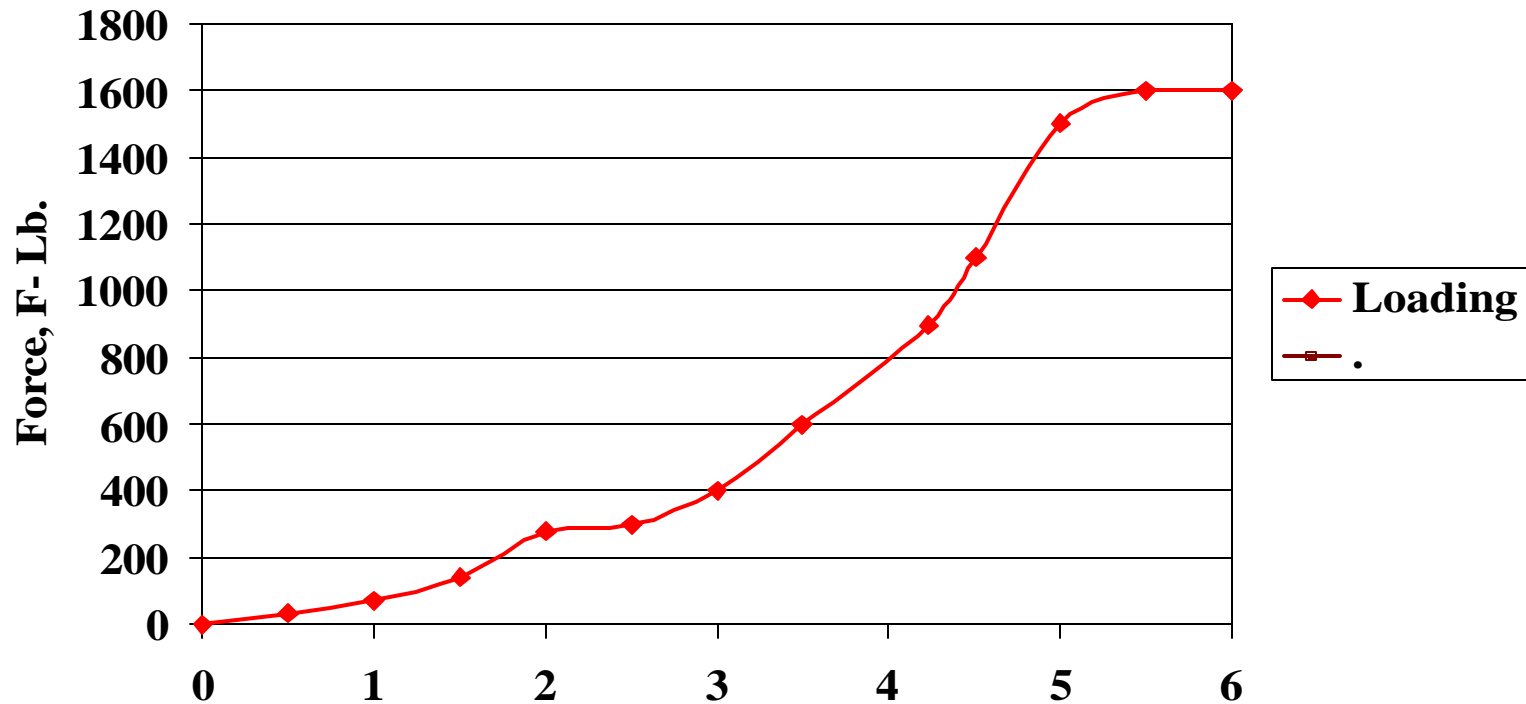
Definition of Penetration





Typical Penetration vs. Force Relationship

Penetration, δ - in.

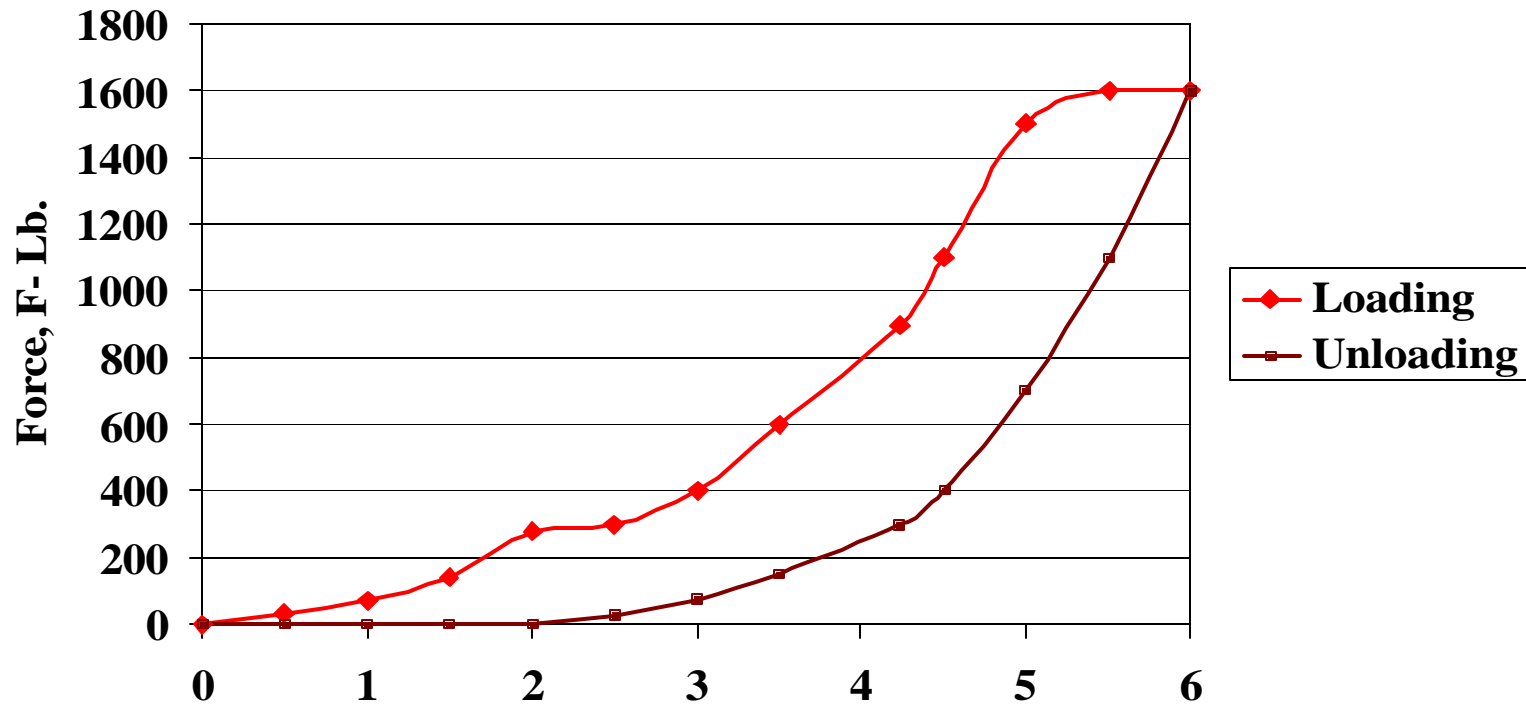


Deformation, in.



Typical Penetration vs. Force Relationship

Penetration, δ - in.



Deformation, in.



Computer Reconstruction of Crashes

Alternative Models

Input Data

Sources of Data

Injury Criteria

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- ATB - lumped mass with string belts
- MADYMO - lumped mass with FEM belts & contacts
- LSDYNA - finite element with rigid skeleton



Comparison of Models

<u>MODEL</u>	<u>COMPUTER</u>	<u>TIME</u>
ATB	PC	30 sec
MADYMO	WORKSTATION	15 min
LSDYNA	POWER CHALLENGE	3-12 hrs

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Approach to Reconstruction

- Use lumped mass models to gain insight into injury mechanisms
- Use cadaver tolerance data to interpret model predictions
- Use FEM models to study injury sensitivity of crash parameters to loads at locations where injury occurs

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Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

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Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
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- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

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Occupant Model

- Validated models of hybrid III dummy available
- Scaling programs available for different size occupants
- No validated human model available
- Simulation is of a dummy not a human!



Input Data Needs for Crash Reconstruction

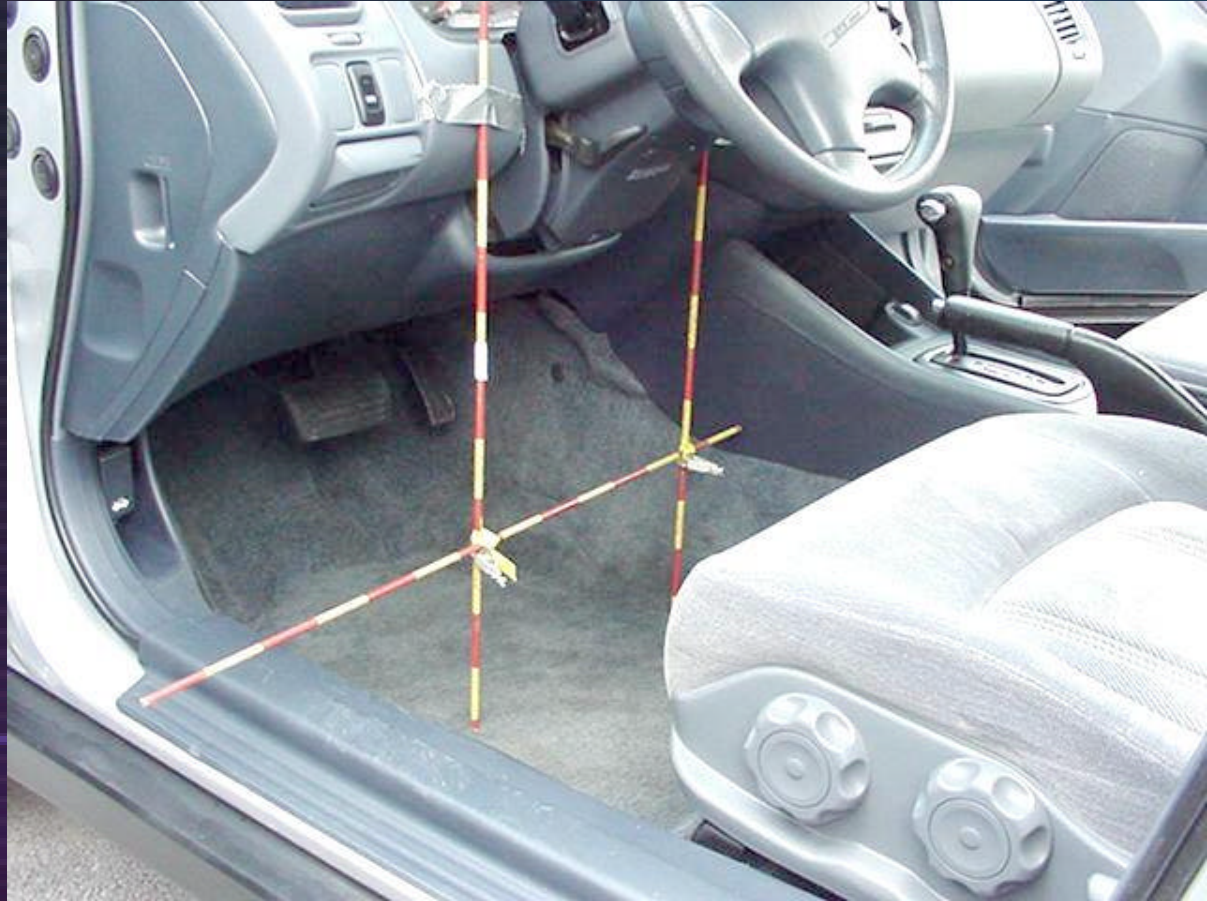
- Occupant Model
- **Vehicle Interior Geometry**
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

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Vehicle Interior Geometry

- Obtained by Direct Measurement





Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

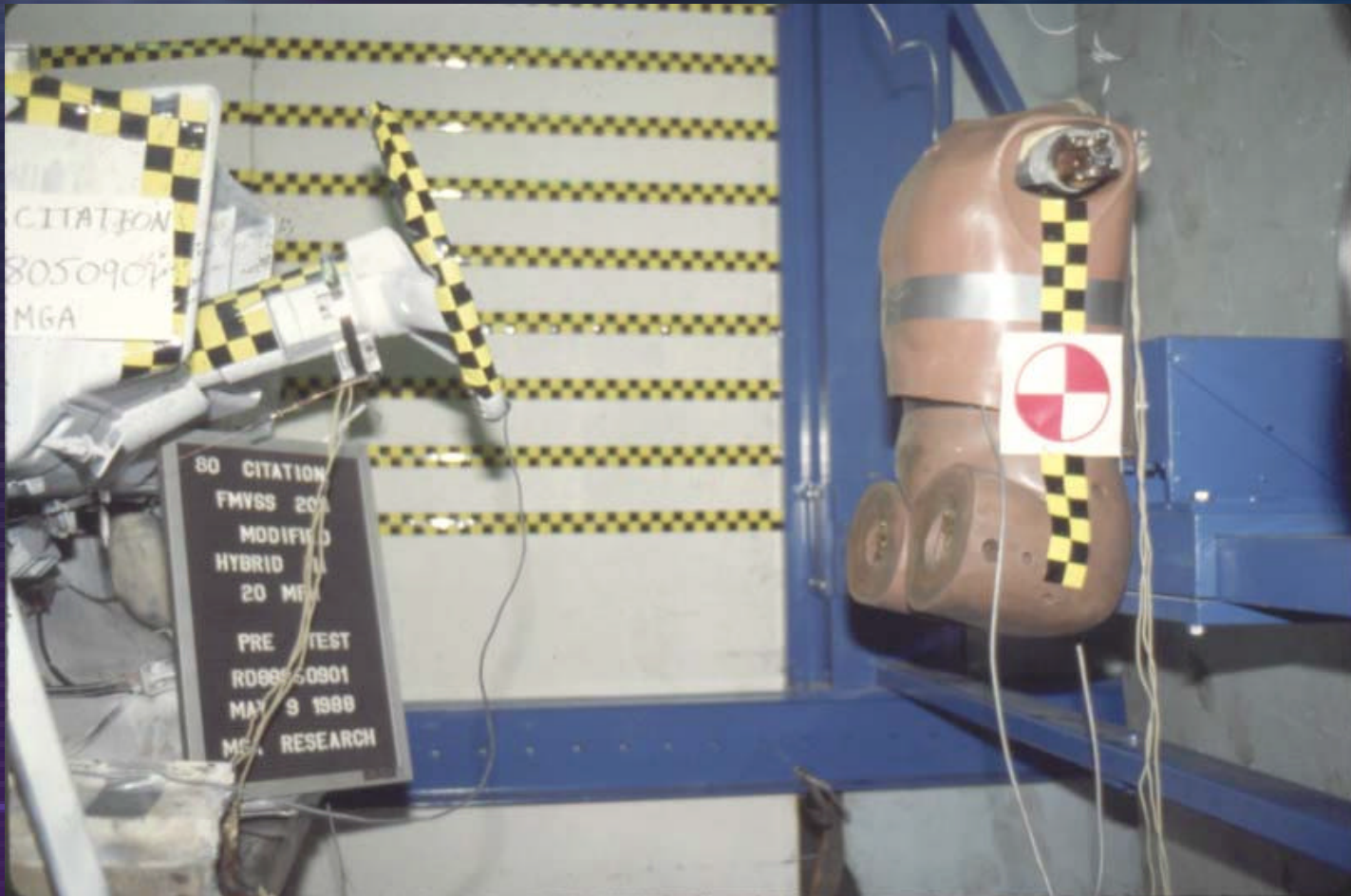


Force Deformation Properties

- Library of properties available from NHTSA research testing
- NCAP and compliance tests of vehicles used to “tune” properties of knee restraints, air bags, and belts

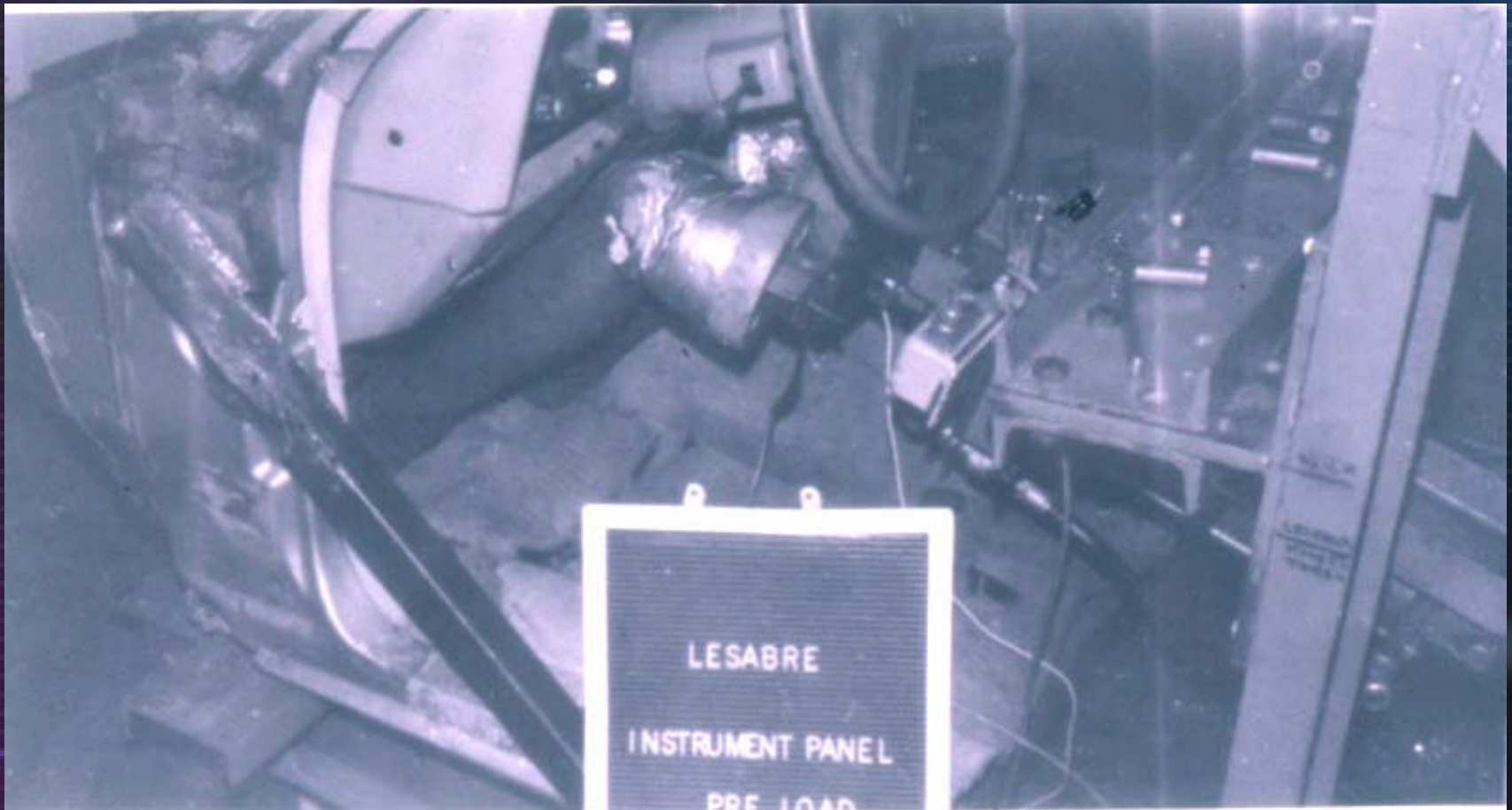
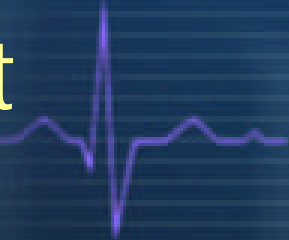


NHTSA Steering Column Dynamic Test





NHTSA Knee Restraint Static Test





Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant

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NCAP and Compliance Tests

- Crash pulse
- Belt slack
- Intrusion history
- Belt and air bag response
- Knee restraint response



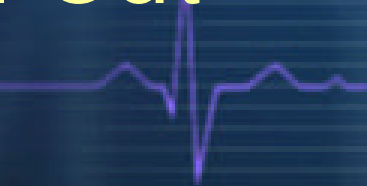
NCAP - 35 mph





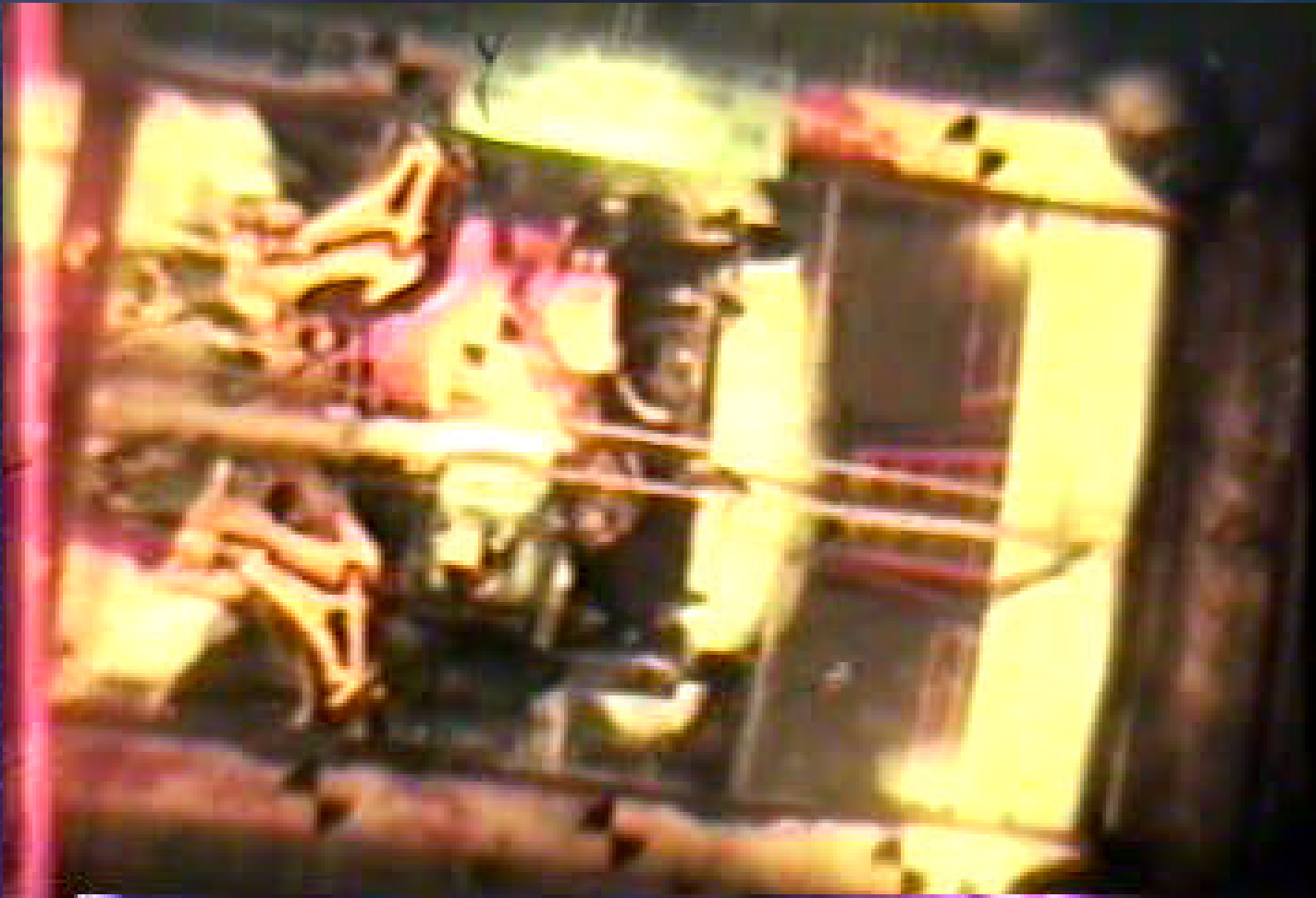
Belt Spool Out

NCAP





NCAP Underside





30 mph Compliance Test



NCAP and Compliance Tests Other Applications



- Provide insights into dummy kinematics
- Provide insights into vehicle performance
- Compliance tests provide air bag response without belts



Input Data Needs for Crash Reconstruction

- Occupant Model
- Vehicle Interior Geometry
- Force Deformation, Friction and Hysteresis of Belts, Air Bag, and Other Contacts
- Crash Pulse (and Intrusion Time - Displacement)
- Initial Position of Occupant



Initial Position

- Driver Interviews
- Crash Investigation
 - Including Louie the Leg
- Trial & Error Modeling



Louie the Leg



Input Data Needs for Crash Reconstruction - Summary

- Occupant model
- Vehicle interior geometry
- Force deformation, friction and hysteresis of belts, air bag, and other contacts
- Crash pulse (and intrusion time - displacement)
- Initial position of occupant



What Lumped Mass Modeling Can Do

- Insight into occupant (dummy) kinematics
- Insight into injury mechanisms
- Sensitivity of crash parameters to modify injury risk
- Direction and approximate magnitude of applied forces



What FEM Models Can Do

- More accurately model human skeletal structure
- More accurately predict the joint forces that produce injury
- More accurately predict the stresses and strains that produce injury



Lower Limb Injury Criteria

- Upper Leg
- Lower Leg



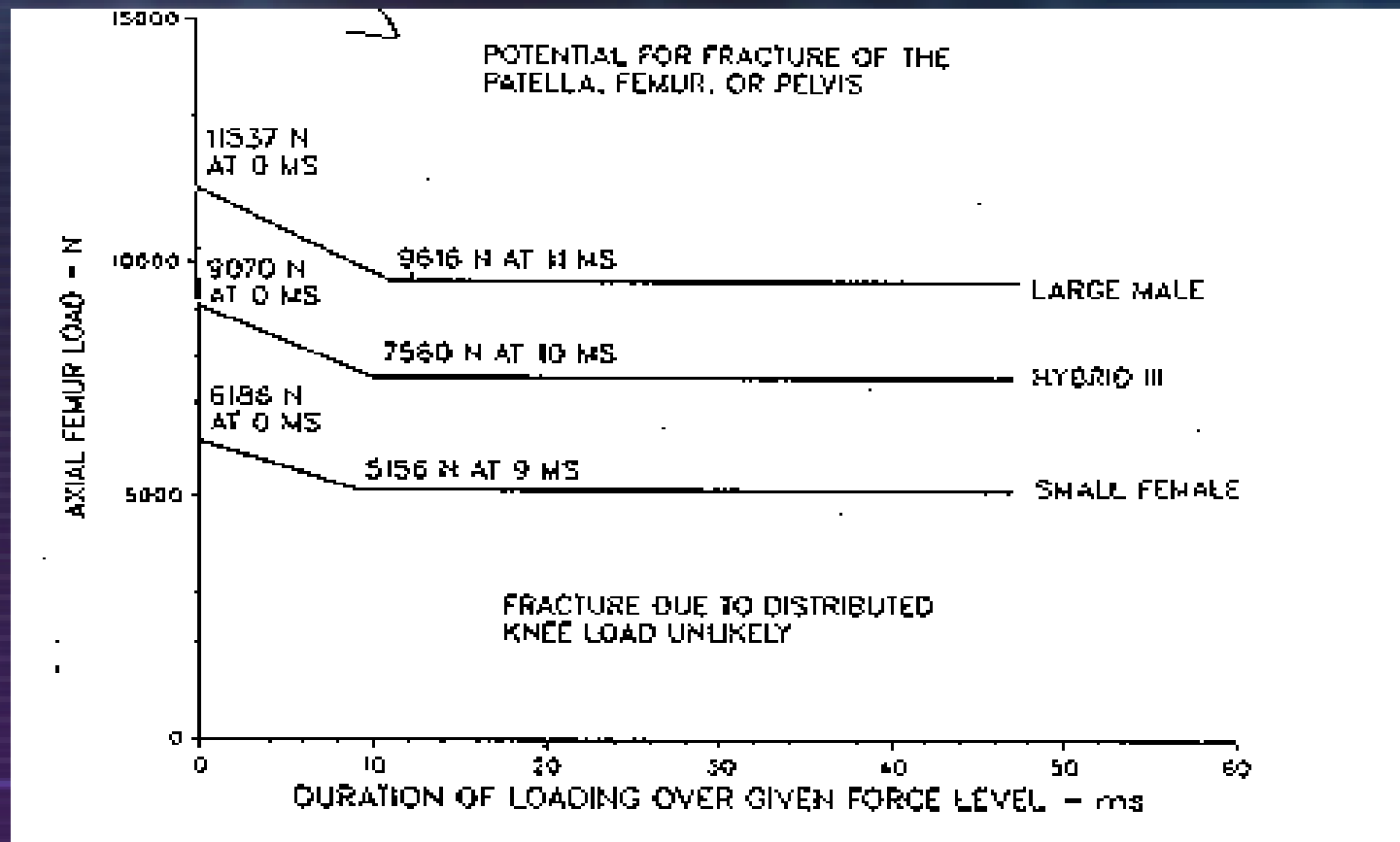
Femur Injury Allowable

Femur Force = 10000 N

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Injury Assessment Curves for Axial Compressive Femur Force Measured With Hybrid III-type Adult Dummies



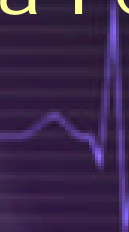


Case #1 Upper Leg Injury

Acetabulum Fracture-Dislocation

Why not a Femur Fracture?

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Case #1

Scene Diagram

Vehicle to barrier crash

Frontal impact

Construction zone, driving
on wrong side of barriers

Clear, dry, dark

Delta-V = 30 mph





Crash Scene - Approach



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Crash Scene - Approach



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Crash Scene - Approach



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New 1992 Volvo



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Case Vehicle - 1992 Volvo

**Use Damage to
Calculate
Crash Severity**

$\Delta V = 30$ MPH





Case Vehicle - 1992 Volvo

- 1990 Volvo 740 GL
- PDOF 12 O'clock
- Delta V – 36.5 mph



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Driver

- 29 y/o male
- Firefighter
- 73" tall, 208 lbs.
- Air bag deployed
- Unbelted
- High suspicion criteria

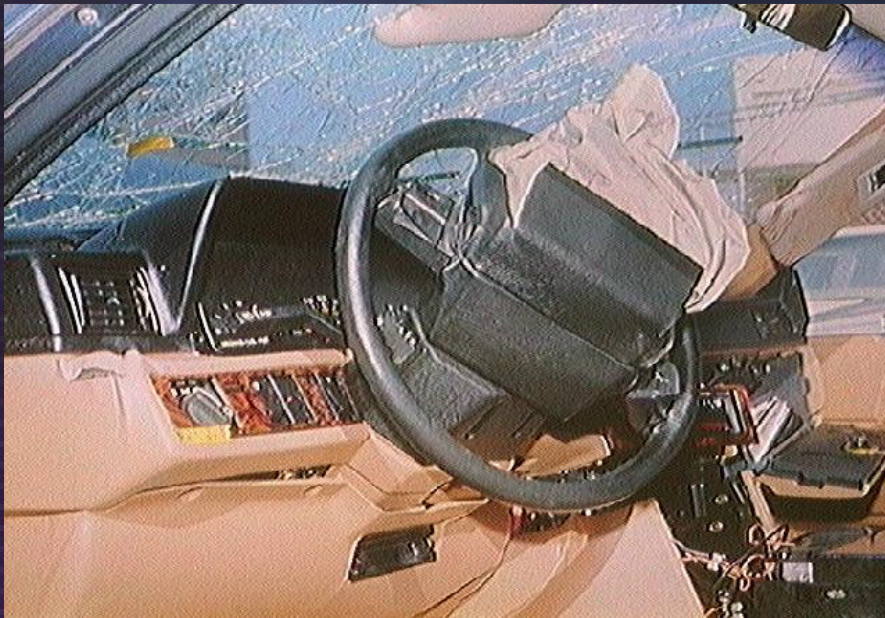


Injury Overview

- Abrasions, Right Forearm, Flank - AIS 1
- Contusions, Right Forearm, Left Thigh – AIS 1
- Lacerations, Scalp, Right Forearm – AIS 1
- Fracture, Right Acetabulum – AIS 3
- Fractures, Left Ribs 5,6,7,8 – AIS 3



Case Vehicle Interior



- Steering wheel deformity – 4.5"
- Intrusions:
 - L Toe Pan – 4"
 - Center Console – 5"
 - L. floor – 4"

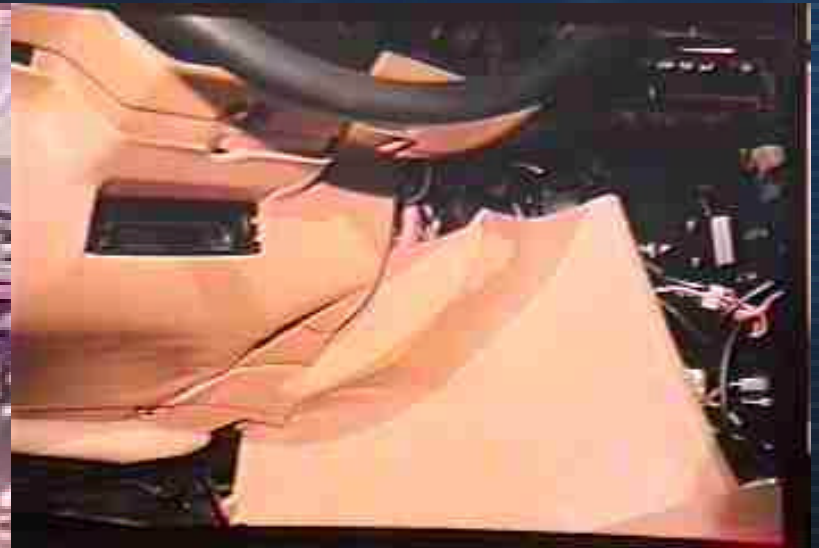


Vehicle Interior- Air Bag Deployed



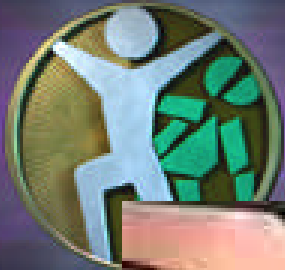


Vehicle Knee Panel



**Location of
Right Leg**

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Vehicle Knee Panel



Right Knee Contact with Knee Restraint

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What was the
mechanism of rib
fractures on left and
head of femur
dislocation on the right?



Examine Same Vehicle in Government Test

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NCAP Test of 1991 Volvo



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Examine Similar Crash

Pole Crash with Ford LTD

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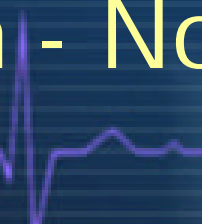
Ford LTD Into a Pole at 30 MPH



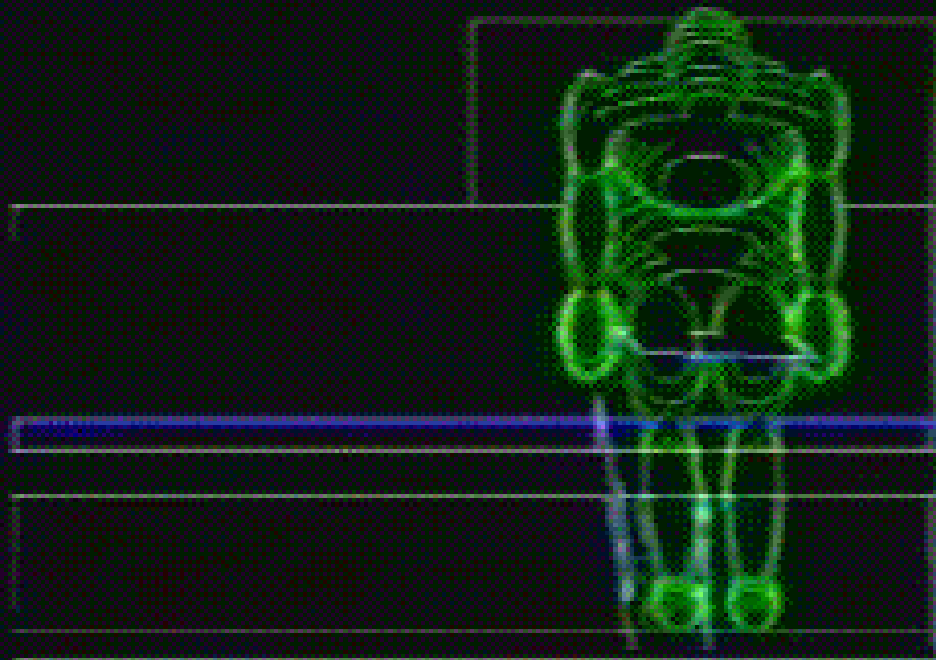
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Reconstruction - No Intrusion



VOLVO - NO INTRUSION
TIME INSECT 0

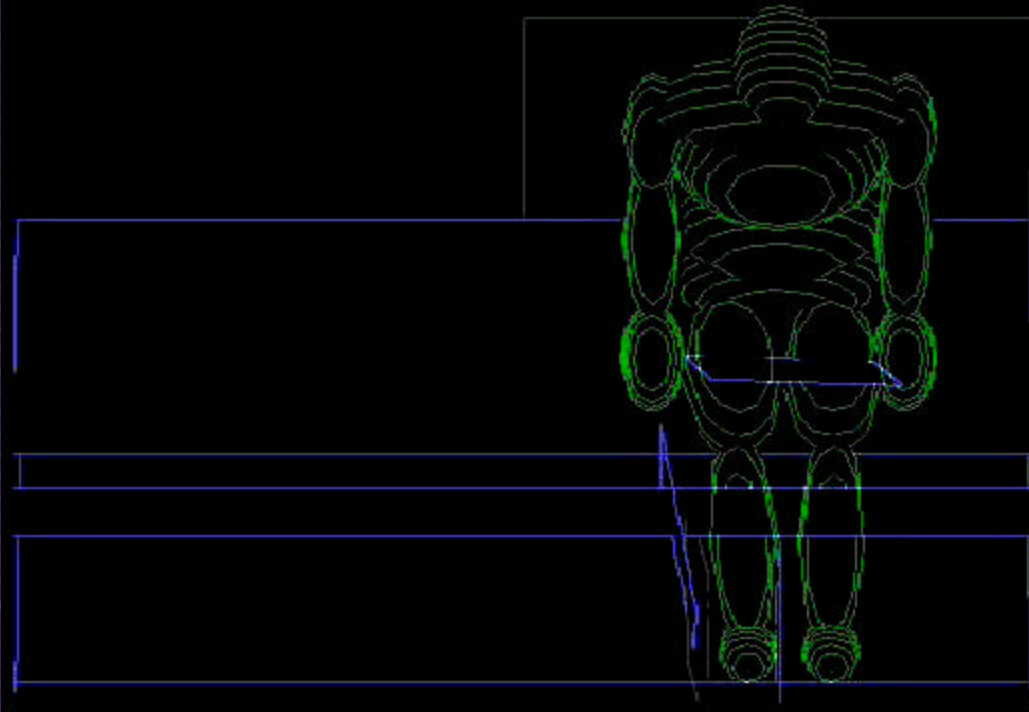




Applied Lump Mass Modeling

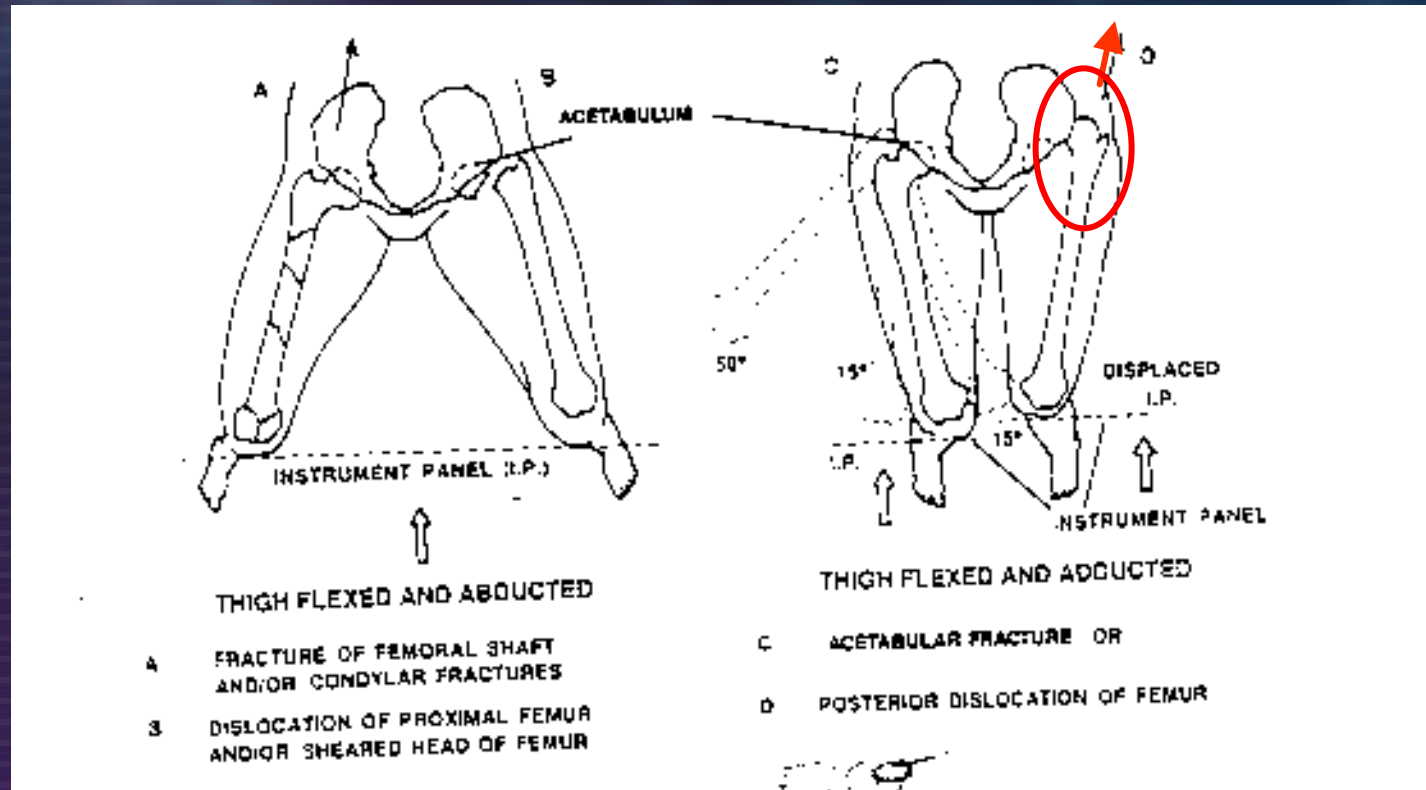


VOLVO RECONSTRUCTION
TIME (MSEC) 0





Adducted Injury - Dislocation





Injury Mechanism

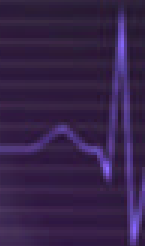
- Direct loading of chest
- Axial loading with external rotation of right hip



Hospital Data



- LOS – 17 days
- Operative procedure: ORIF of right acetabulum
- Hospital charges: \$47,003.08
- Discharged home



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Conclusions and Summary

- Air bag mitigated life threatening chest injuries.
- Knee protection good
- Lower extremity exposure to injury still high
- Adducted right leg increased vulnerability to dislocation



Lower Leg Injuries (Below the Knee)

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Tibia Tolerance Mertz Criteria

- Axial Compression (50th %) - 8000 N
- 5th % - 5104 N
- 95th% - 9840 N



MECHANISMS OF FOOT/ANKLE INJURIES

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Ankle Injury Tolerance

Malleolar Fracture

- “The Role of Axial Loading in Malleolar Fracture”, Funk, Tourret, George, and Crandall, SAE 2000-01-0155
- Produced malleolar fracture from axial impacts of cadaver feet with 16 cm of intrusion
- Varied initial foot position
- Observed subsequent inversion or eversion
- Results ----

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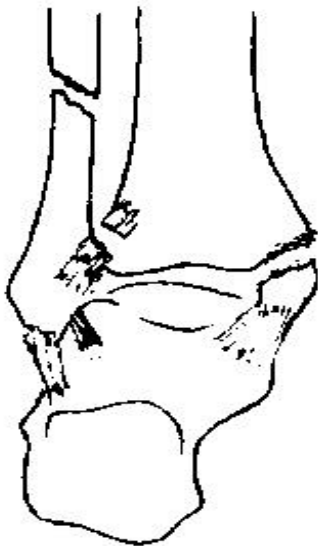
Cadaver Test Results

<u>Initial Position</u>	<u>Direction of Bending</u>	<u>Location of Fracture</u>	<u>Force at Fracture</u>
10° Inversion	Inversion	Lateral	5473N
30° Pf	Eversion	Medial	7929N
Neutral	Eversion	Medial	7349N

Eversion

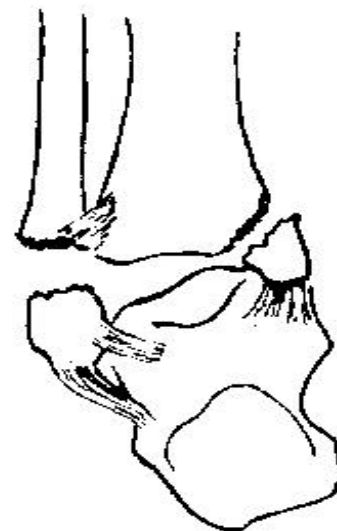
Inversion

Lateral



Medial

Lateral

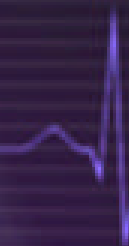


Medial



Case Presentation

Lower Leg Injuries (Below the Knee)



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Case #2

Scene Diagram



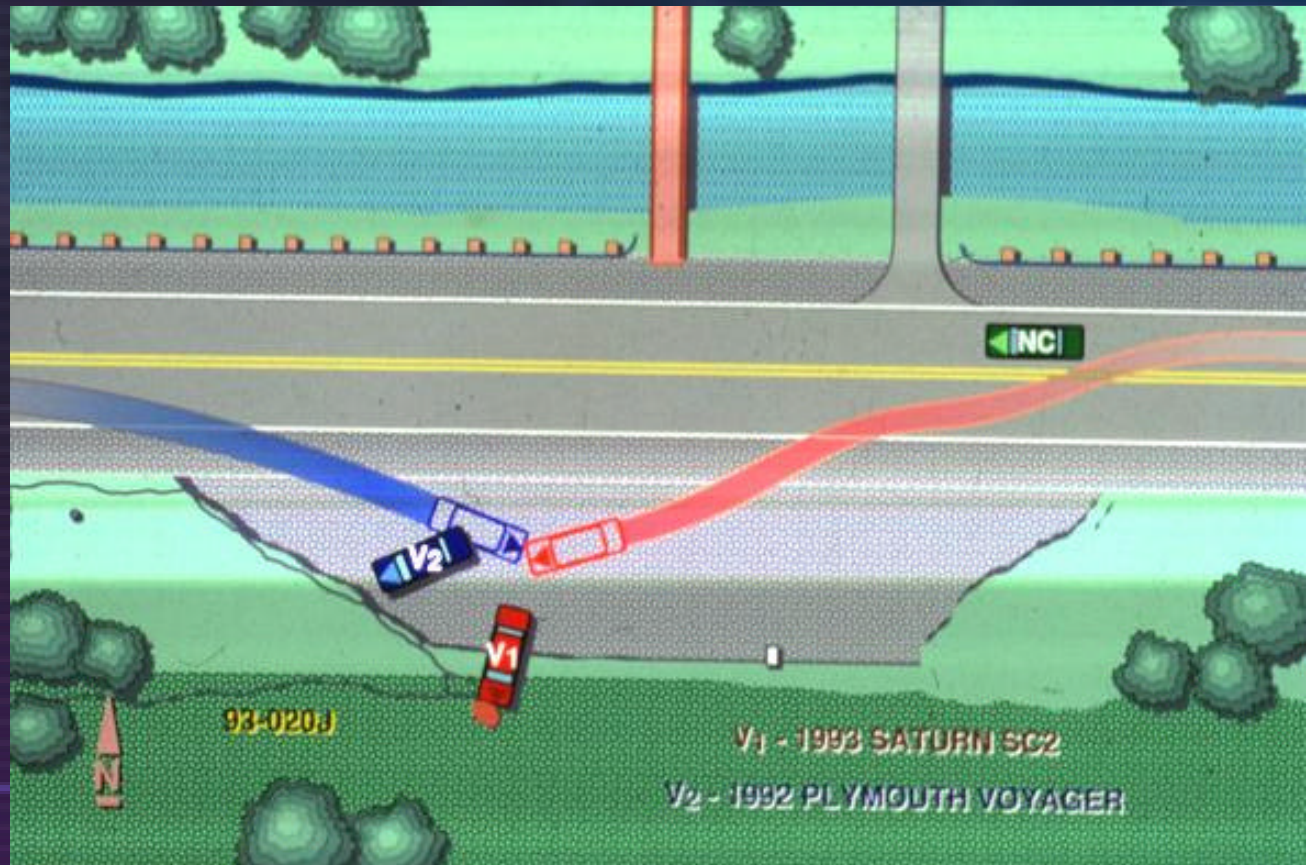
Car-to-Car Crash

Frontal Offset

Rural 2-Lane
Road

Clear, Daylight

Passing Maneuver





Case Vehicle

Frontal Offset
1 O'clock
20° Oblique
DeltaV- 32 mph
1993 Saturn SC2

POV - Plymouth
Minivan (1992)





Case Vehicle



1" of Left Toe Pan Intrusion





Vehicle Interior

Steering Wheel
Removed by
Rescue Squad





Case Vehicle Driver

53 Year Old Female
5'2"; 205 lbs.

Did not meet
trauma criteria

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Driver Injuries

Liver Lac - AIS 2

Rib Fx - AIS 2

Tear, Renal Artery AIS-3

Burn Right Arm - AIS-2

Open Fx R. Ankle - AIS-2

Open Fx. L Ankle - AIS-2



Driver Injuries

Liver Lac - AIS 2

Rib Fx - AIS 2

Tear, Renal Artery AIS-3

Burn Right Arm - AIS-2

Open Fx R. Ankle - AIS-2

Open Fx. L Ankle - AIS-2

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Chest Injuries

Liver Laceration - AIS 2

Rib Fracture - AIS 2

Apply Lumped Mass Model -

- 1 - Examine Chest Loading by 2-Point Belt
- 2 - Examine the Loading of Lower Limb Injuries

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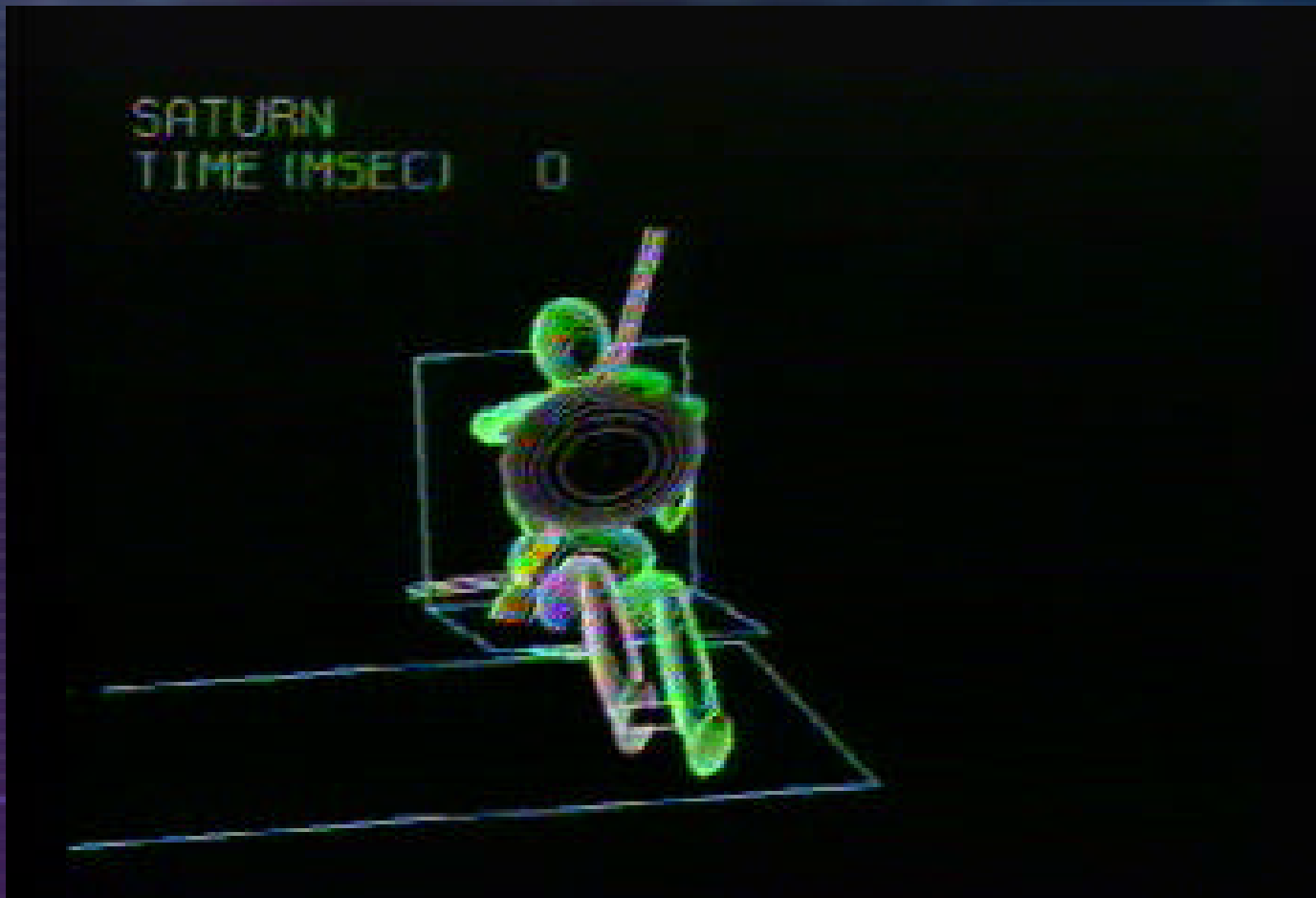


Computer Reconstruction of Occupant Loading

- Input Vehicle Acceleration
- Model Occupant Using ATBModel
 - Lumped Mass Model (Like MADYMO)
- Model With Air Bag & Without Intrusion
- Add Intrusion
- Retain Air Bag Forces, but Remove it Graphically to Show Driver Kinematics

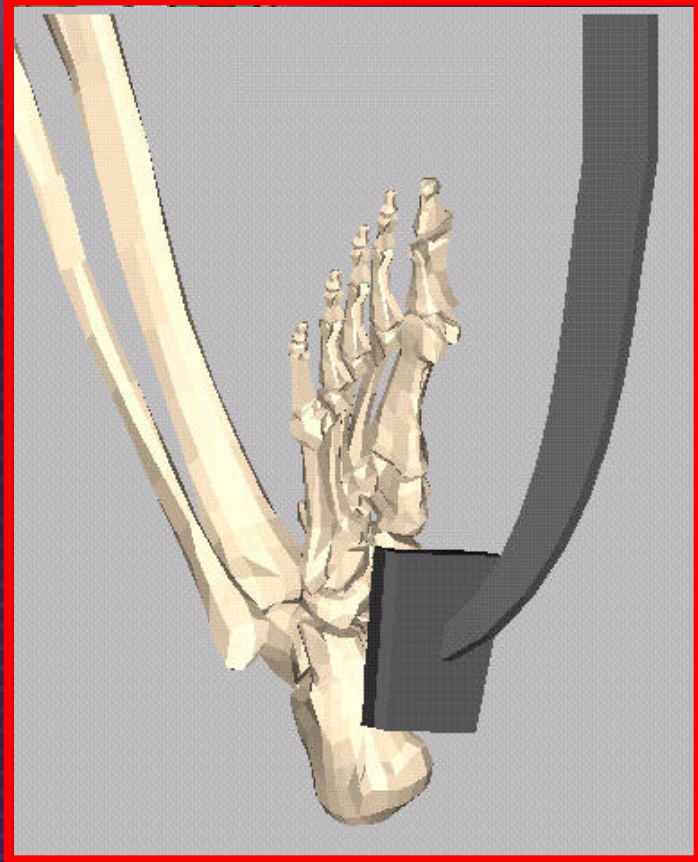


Occupant Motion -Lower Limbs





Right Ankle Injuries



Right -Open Pilon Fracture
Dorsiflexion Mode

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Vehicle Brake Pedal Deformation

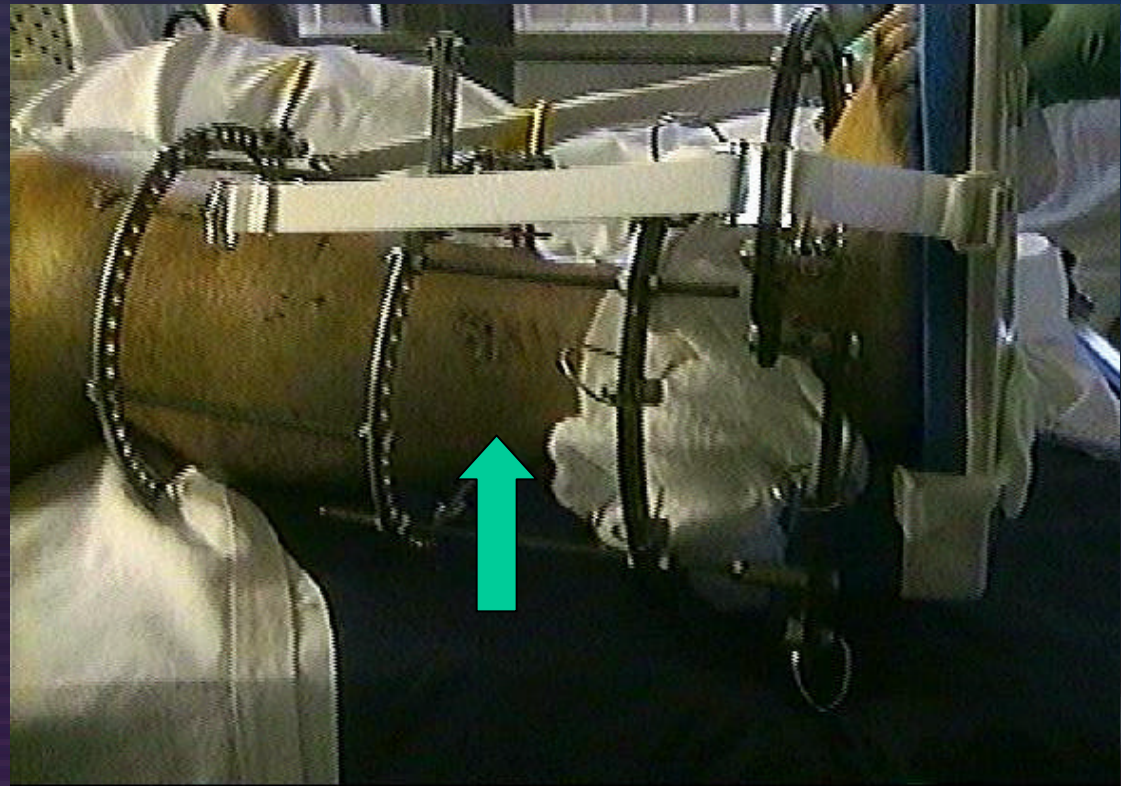
2" Lateral Shift

1" Toeplate
Intrusion





Right Leg Abrasions



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Abrasion Source





Locating Lower Limbs



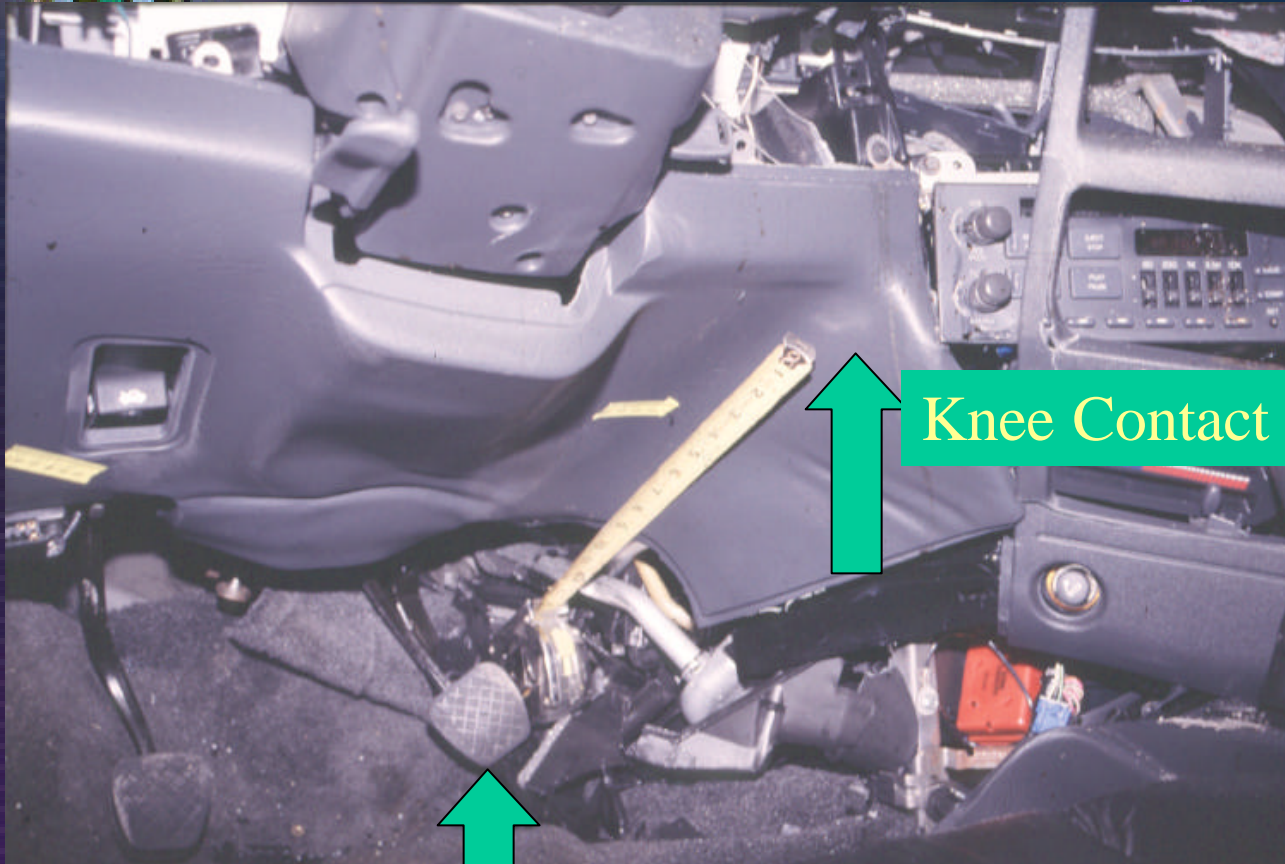


Position of Right Foot





Right Limb Contacts

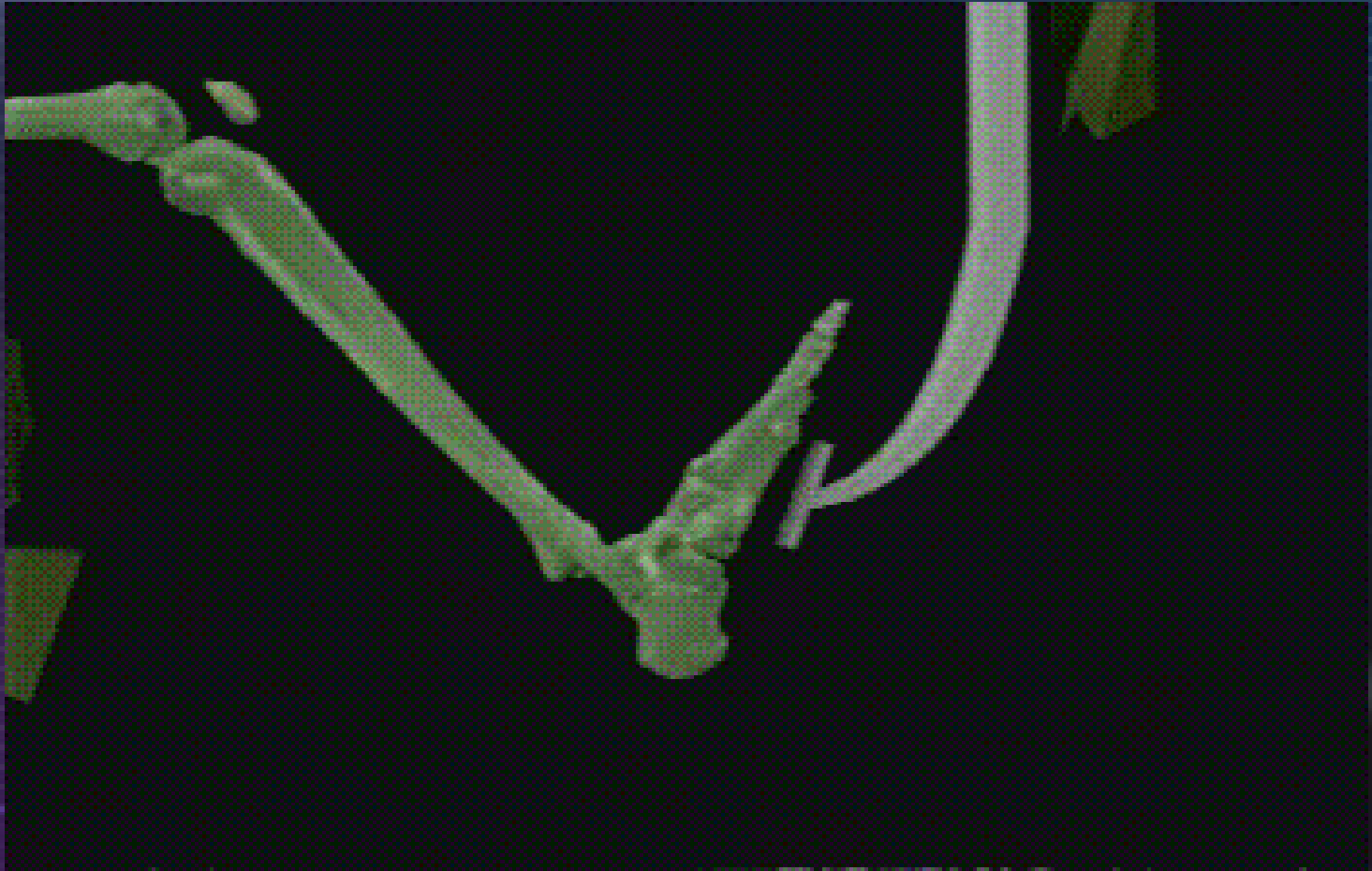


Evidence of Bracing

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Right Foot Simulation

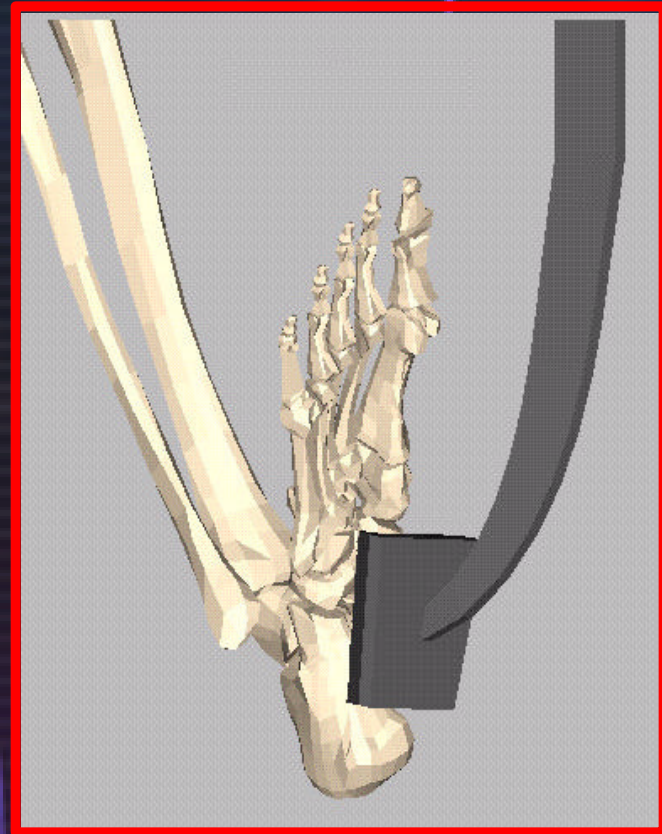




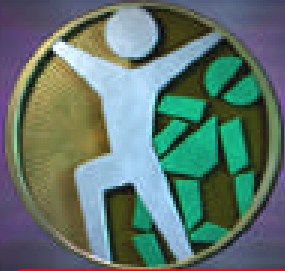
Case Simulation Results

Right Ankle Injury
Caused by Severe
Bracing and Brake Pedal
Loading

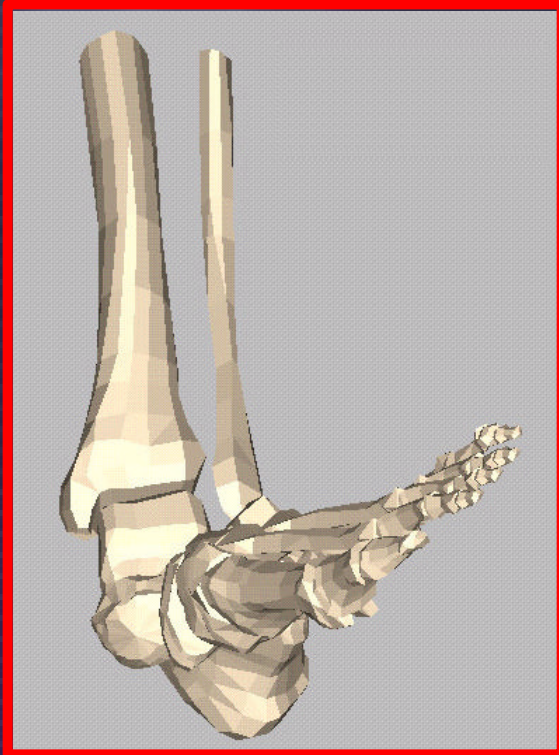
Right - 48° dorsiflexion
Tibia force = 11.2 kN



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Left Ankle Injury

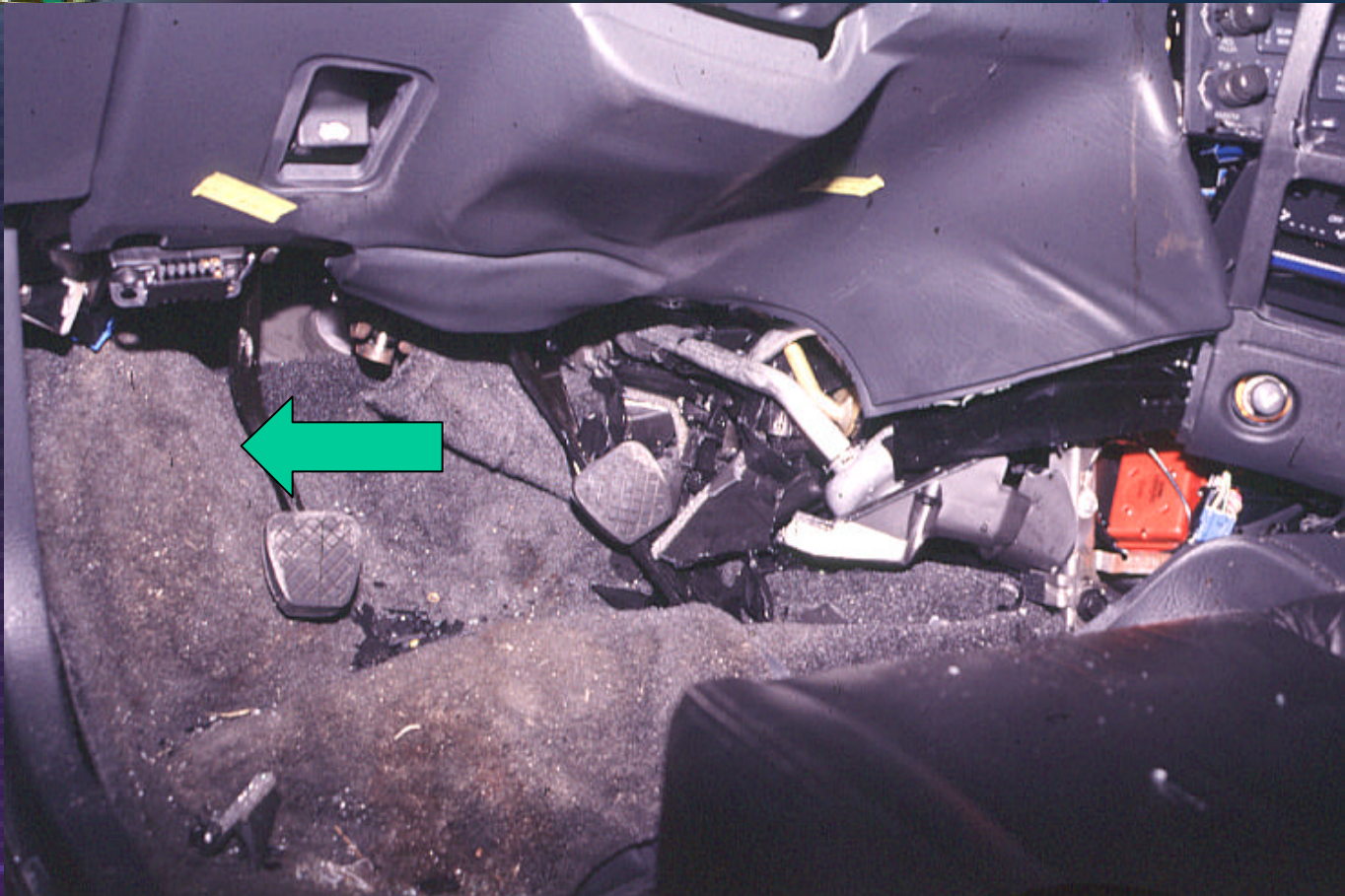


Left - Open Fracture/dislocation
Talo-Calcarneo-navicular Joint
Eversion Mode

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Eversion injury with
minor toepan intrusion?





Apply Crash Tests & Modeling to Answer the Question

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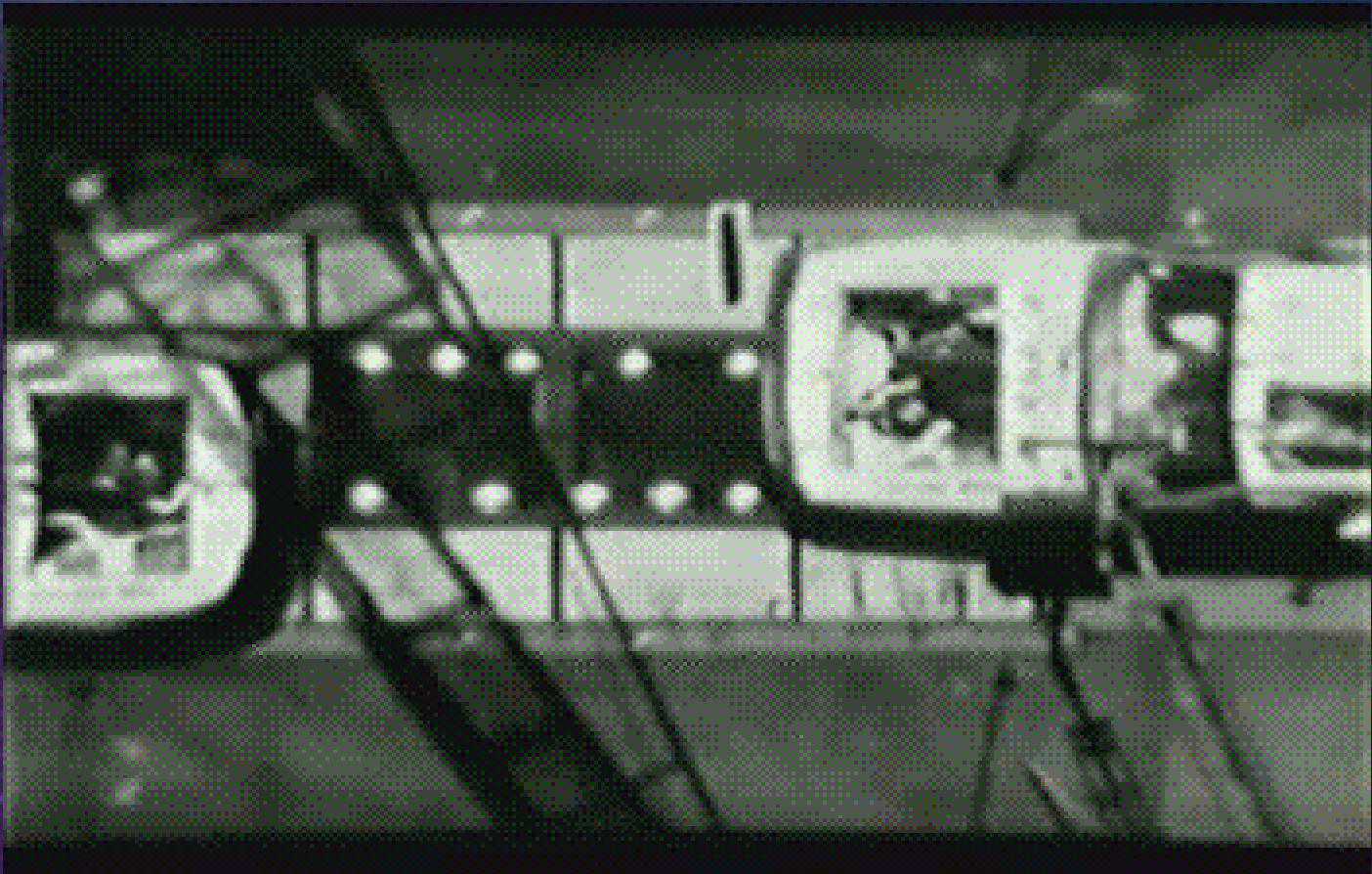


Offset Crash Tests from NHTSA & IIHS Files

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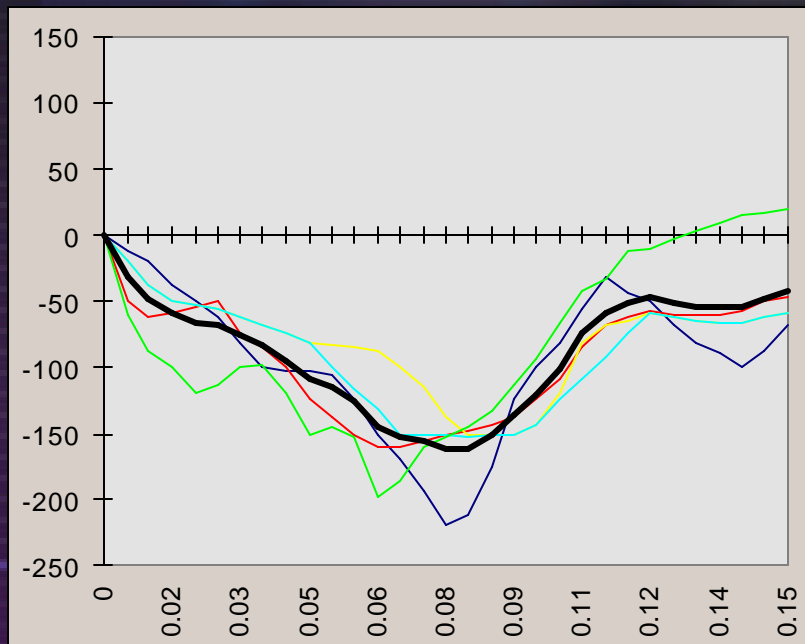
Force Vector in Car-to-Car Offset Crash



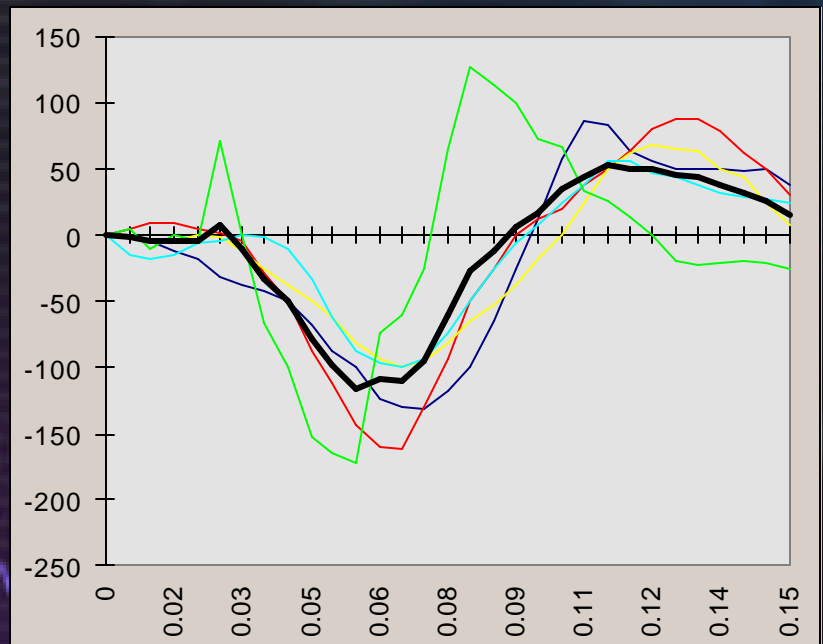


Crash Pulse Determination Car-to-Car Offset Frontal Crash Accelerations

Longitudinal Pulse



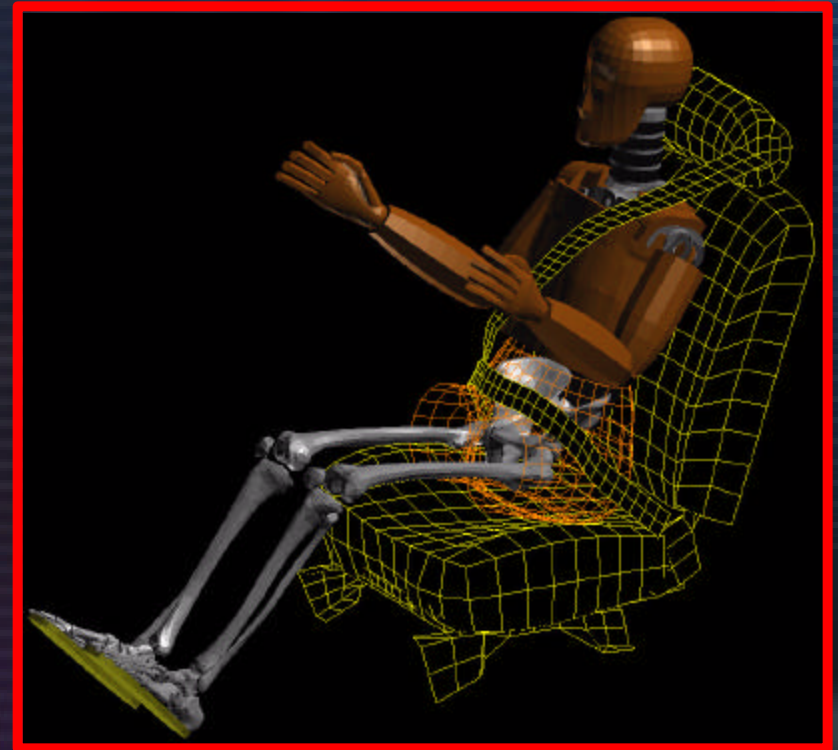
Lateral Pulse





Computer F-E Model of Human Lower Limbs

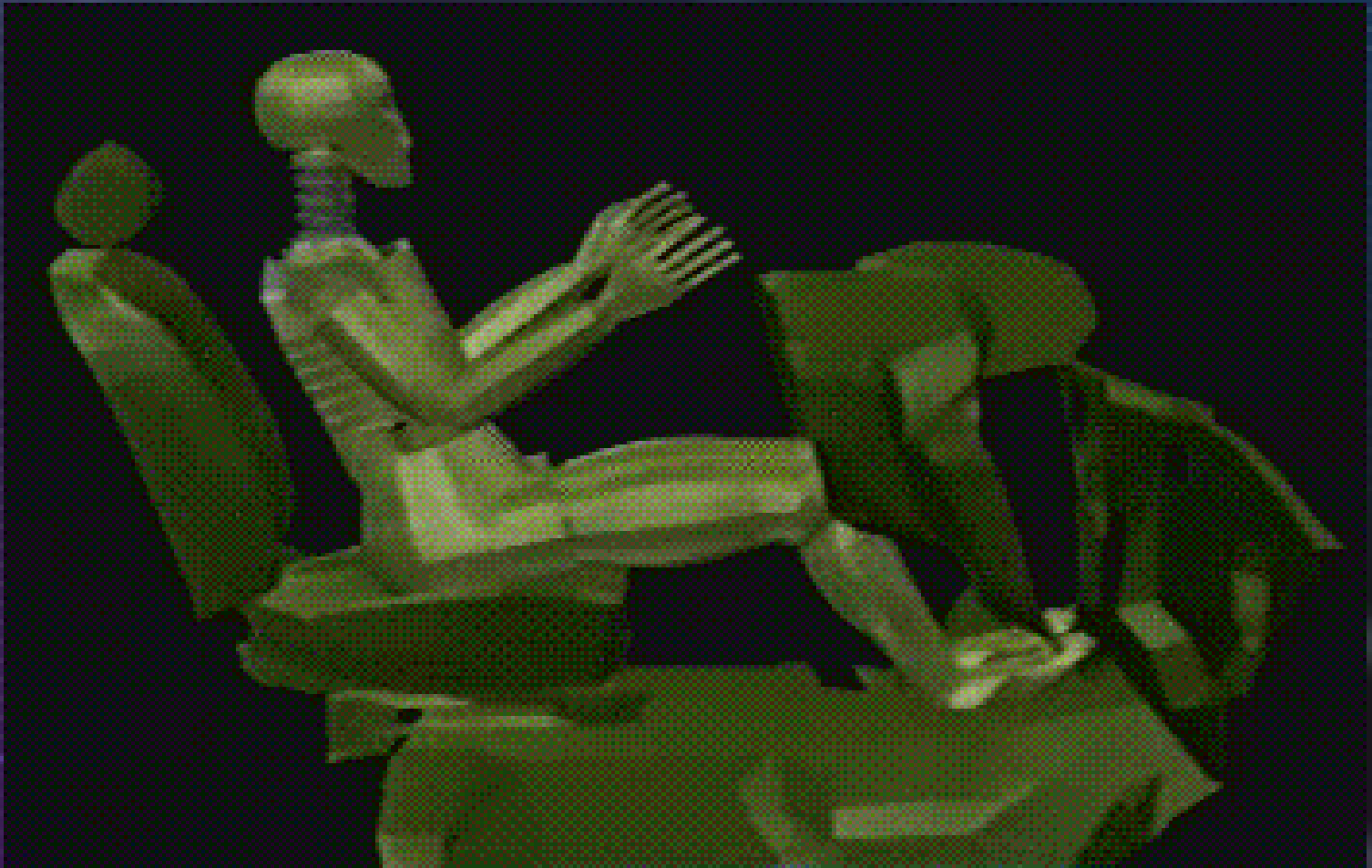
- FEM Model of Dummy
- Validation
- FEM Model of Human Limbs
- Validation
- Combine Models
- Apply to Injury Mechanisms



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Dummy/Leg FEM Model in Frontal Offset Crash





Case Simulation Results



Left ankle - Eversion

- High axial load
- Crash pulse with lateral component
- Uneven floor

Tibia force = 8.6 kN

Left - 53° Eversion

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Summary of Injuries & Causes

- Right ankle - dorseflexion from braking
- Left ankle - eversion from axial load, lateral component in crash pulse, & uneven floor
- Liver - shoulder belt loading
- Abdominal aorta - bracing



Principal Findings

- Shoulder belts w/o lap belts induce liver injuries
- Eversion injuries are possible without significant toepan intrusion
- Lateral acceleration acts to increase vulnerability of ankle joint to inversion/eversion



Conclusions

- Crash reconstruction improves understanding of injury mechanisms
- Application of crash tests and analysis aid in understanding injuries
- Eversion injuries can occur with no intrusion
 - High Axial Load
 - Lateral Acceleration
 - Uneven floor